5TH SIVAS INTERNATIONAL CONGRESS OF SCIENTIFIC RESEARCH AND INNOVATION

THE PROCEEDINGS BOOK

September 25–27, 2026

Sivas University of Science and Technology, Sivas, Türkiye

EDITOR
Prof. Dr. Kağan KÖKTEN



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Prof. Dr. Kağan KÖKTEN

Date: 20.10.2026

Liberty Publishing House

Water Street Corridor New York, NY 10038

www.libertyacademicbooks.com

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ISBN: 979-8-89695-588-7

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CONGRESS ID

CONGRESS TITLE

5TH SIVAS INTERNATIONAL CONGRESS OF SCIENTIFIC RESEARCH AND INNOVATION

DATE AND PLACE

25–27 September 2026 · Sivas University of Science and Technology, Sivas, Türkiye

CONGRESS STATISTICS

TOTAL ACCEPTED PAPERS	TOTAL REJECTED PAPERS	TOTAL PAPERS FROM TÜRKIYE	TOTAL PAPERS FROM INTERNATIONAL PARTICIPANTS
250	**59**	**123**	**127**

PARTICIPANT COUNTRIES (34)

Türkiye, India, Nigeria, Afghanistan, Algeria, Pakistan, Iran, Tunisia, Morocco, Indonesia, Romania, Lebanon, Libya, Republic of Moldova, Ukraine, Italy, Vietnam, Kosovo, Uganda, Niger Republic, Mexico, Azerbaijan, Albania, Republic of Guinea, North Macedonia, USA, Tanzania, Oman, Kyrgyzstan, TRNC, Bulgaria, Russia, Malaysia, Iraq

EVALUATION PROCESS

› All applications have undergone a double-blind peer review process

PRESENTATION

› Oral Presentations

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5th Sivas International Congress of Scientific Research and Innovation

25–27 September 2026 · Sivas University of Science and Technology

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Ankara Time: 09:30-10:30

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Prof. Dr. Muhammad ASIM
Sivas University of Science and Technology, Türkiye

IN PERSON SESSIONS

DATE: 25.09.2026

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DATE
25 September 2026

VENUE
Sivas University of Science and Technology

TIME 10:30-12:30

HEAD OF SESSION: Asst. Prof. Celal ALAGÖZ

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Fahrettin Burak İLDEN Celal ALAGÖZ Mehmet KURNAZ	*Sivas University of Science and Technology, Türkiye*	**ESTIMATION OF BODY MASS INDEX FROM 12-LEAD ECG SIGNALS USING MINIROCKET FEATURES AND BAGGED ENSEMBLE NEURAL NETWORKS**
Mehmet KURNAZ Asst. Prof. Celal ALAGÖZ Tuna Sencer FİGANKAPLAN	*Sivas University of Science and Technology, Türkiye*	**FAST-TCN-FUSION: A MULTI-SCALE TCN AND FFT-BASED ADAPTIVE TIME–FREQUENCY FUSION ARCHITECTURE FOR TIME SERIES CLASSIFICATION**
Assoc. Prof. Dr. Emre BÜLBÜL Assoc. Prof. Dr. Mehmet DOĞAN	*Erciyes University, Türkiye*	**THE IMPORTANCE AND USE OF ADRENALINE AUTO-INJECTORS IN ANAPHYLAXIS**
Assoc. Prof. Dr. Mehmet DOĞAN Assoc. Prof. Dr. Emre BÜLBÜL	*Erciyes University, Türkiye*	**EVALUATION OF THE SUICIDE CASES OF THE LAST 10 YEARS IN TÜRKİYE**
Asst. Prof. Dr. Yunus ÇELİK Asst. Prof. Dr. Onur ERKAN	*Sivas University of Science and Technology, Türkiye* *Bilecik Şeyh Edebali University, Türkiye*	**PERFORMANCE EVALUATION OF A 2D LBM SOLVER FOR FLOW AROUND CYLINDERS ACROSS VARIOUS ASPECT RATIOS**
Asst. Prof. Dr. Onur ERKAN	*Bilecik Şeyh Edebali University, Türkiye*	**A NUMERICAL ASSESSMENT OF AN INCLINED FLAT PLATE WITH A SEMICIRCULAR CYLINDER FOR FLOW-INDUCED ENERGY HARVESTING**
Asst. Prof. Dr. Aydın GÜNEŞ	*Abdullah Gül University, Türkiye*	**INVESTIGATION OF PRODUCING COMPOSITE MATERIALS FROM WASTE ALUMINUM AND CUSN10 BRONZE CHIPS BY HOT EXTRUSION**
Tacettin ERGENÇ	*Independent Researcher, Türkiye*	**CONTEXT-AWARE MACHINE LEARNING FOR ANOMALY DETECTION IN NANOINDENTATION CURVES: SAMPLE-GROUPED VALIDATION**
Kübra AYHAN TANYILDIZ Ferhat DELİBAŞ Göksel ARAS Assoc. Prof. Dr. Ebru YABAŞ	*Sivas Cumhuriyet University, Türkiye*	**DESIGN AND DEVELOPMENT OF NEXT-GENERATION MODULAR STORAGE SYSTEMS**
Ömer KOÇOĞLU Ferhat DELİBAŞ Göksel ARAS Assoc. Prof. Dr. Ebru YABAŞ	*Sivas Cumhuriyet University, Türkiye*	**FROM CORRECT POSITIONING TO STANDARDIZED PRODUCTS IN ROBOTIC WELDING: THE ROLE OF WELDING FIXTURES IN THE PRODUCTION PROCESS**

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VENUE
Sivas University of Science and Technology

DATE
25 September 2026

TIME: 10:30-12:30

HEAD OF SESSION: Prof. Dr. Sabit HOROZ

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Res. Asst. Aslıhan ANTER ALTAN Prof. Dr. Elif ORHAN	*Gazi University, Türkiye*	**EFFECT OF INCIDENT OPTICAL POWER DENSITY ON THE PHOTORESPONSE OF A DOPED GRAPHENE QUANTUM DOT-BASED HETEROJUNCTION**
Dr. Zeynep BERKTAŞ Prof. Dr. Elif ORHAN	*Gazi University, Türkiye*	**PHOTODETECTION PERFORMANCE OF A BISMUTH-DOPED GRAPHENE QUANTUM DOT-BASED HETEROJUNCTION AFTER 24 MONTHS**
Res. Asst. Melis Irmak AYDIN Prof. Dr. Ayşe BAYRAKÇEKEN	*Atatürk University, Türkiye*	**HETEROATOM DOPING OF PEM FUEL CELL ELECTROCATALYST MATERIALS**
Asst. Prof. Dr. Yılmaz MERT Asst. Prof. Dr. İbrahim KORKUT	*Sivas University of Science and Technology, Türkiye*	**SYNTHESIS OF HCL-DOPED POLYANILINE BY CHEMICAL OXIDATIVE POLYMERISATION AND ITS ADSORPTIVE PERFORMANCE FOR METHYLENE BLUE**
Emre BİÇER Tülay AKSOY	*Ankara University, Türkiye* *Sivas University of Science and Technology, Türkiye*	**OXIDE-BASED SOLID ELECTROLYTES FOR SOLID-STATE LITHIUM BATTERIES: ION TRANSPORT, MATERIAL CLASSES, AND PROCESSING STRATEGIES**
Assoc. Prof. Dr. Salih ÖZBAY	*Sivas University of Science and Technology, Türkiye*	**THERMODYNAMIC PREDICTION OF POLYPROPYLENE–SOLVENT/NONSOLVENT INTERACTIONS USING HANSEN SOLUBILITY PARAMETERS AND FLORY–HUGGINS THEORY**
İpek BALNAN Prof. Dr. Sabit HOROZ	*Sivas University of Science and Technology, Türkiye* *Sivas University of Science and Technology; Sivas Cumhuriyet University, Türkiye*	**CDS SEMICONDUCTOR IN PHOTOCATALYTIC APPLICATIONS: A MINI REVIEW**
İpek BALNAN Prof. Dr. Sabit HOROZ	*Sivas University of Science and Technology, Türkiye* *Sivas University of Science and Technology; Sivas Cumhuriyet University, Türkiye*	**STRUCTURAL AND OPTICAL CHARACTERIZATION OF CU-DOPED ZNS NANOPARTICLES SYNTHESIZED BY SOL-GEL METHOD AT DIFFERENT ANNEALING TEMPERATURES**

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VENUE
Sivas Universty of Science and Technology

DATE
25 September 2026

TIME: 10:30-12:30

HEAD OF SESSION: Assoc. Prof. Dr. Hale GÜNAÇTI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Res. Asst. Hüseyin AYDIN Prof. Dr. Müdahir ÖZGÜL	*Atatürk University, Türkiye*	**THE EFFECTS OF TOPOGRAPHIC FACTORS ON SOIL ORGANIC CARBON FRACTIONS AND STABILIZATION MECHANISMS**
Res. Asst. Erhan YOLDAŞ Prof. Dr. Orhan DENGİZ Assoc. Prof. Dr. Fikret SAYGIN	*Sivas University of Science and Technology, Türkiye* *Ondokuz Mayıs University, Türkiye*	**GIS-BASED ASSESSMENT OF SOIL EROSION RISK IN BAYBURT PROVINCE USING THE ICONA MODEL**
Assoc. Prof. Dr. Hale GÜNAÇTI	*Sivas University of Science and Technology, Türkiye*	**FUNGAL DISEASES OF TOMATO (SOLANUM LYCOPERSICUM L.): MAJOR PATHOGENS, SYMPTOMS AND MANAGEMENT STRATEGIES**
Müjgan ULUSOY Dr. Tülin SARIGÜL ERTEK Assoc. Prof. Dr. Hale GÜNAÇTI	*Sivas University of Science and Technology, Türkiye* *Directorate of Plant Protection Central Research Institute, Türkiye*	**BIOCONTROL POTENTIAL OF SOME TRICHODERMA SPP. AGAINST SOME FUSARIUM SPP. AND MONILIA LAXA**
İkbal TOPBAŞ Dr. Tülin SARIGÜL ERTEK Assoc. Prof. Dr. Hale GÜNAÇTI	*Sivas University of Science and Technology, Türkiye* *Directorate of Plant Protection Central Research Institute, Türkiye*	**DETERMINATION OF IN VITRO BIOCONTROL EFFICACY OF SOME TRICHODERMA SPP. AGAINST FUSARIUM OXYSPORUM**
Hatice DOĞAN Assoc. Prof. Dr. Hale GÜNAÇTI	*Sivas University of Science and Technology, Türkiye*	**IMPORTANCE OF WHEAT PRODUCTION AND EVALUATION OF PLANT PROTECTION PROBLEMS IN SİVAS**

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VENUE
Sivas University of Science and Technology

DATE
25 September 2026

TIME: 14:00-16:00

HEAD OF SESSION: Assoc. Prof. Dr. Asuman KAPLAN EVLİCE

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Gökçe ÖZDEMİR	*Sivas Cumhuriyet University, Faculty of Veterinary Medicine, Department of Animal Science, Türkiye*	**PRECISION LIVESTOCK FARMING: AN APPROACH TO SUPPORTING SUSTAINABLE LIVESTOCK FARMING AND REDUCING ENVIRONMENTAL RISKS**
Res. Asst. Erturan YETİŞKİN Prof. Dr. Orhan DENGİZ Assoc. Prof. Dr. Fikret SAYGIN	*Sivas University of Science and Technology, Türkiye* *Ondokuz Mayıs University, Türkiye*	**GIS-BASED ASSESSMENT OF POTENTIAL AND ACTUAL SOIL EROSION RISK USING THE CORINE MODEL: A CASE STUDY OF THE ERFELEK WATERSHED**
Asst. Prof. Dr. Mehmet BEDİR Prof. Dr. Faheem Shahzad BALOCH	*Sivas University of Science and Technology, Türkiye* *Mersin University, Türkiye*	**EFFECTS OF DROUGHT STRESS ON SEED QUALITY IN CEREAL CROPS**
Asst. Prof. Dr. Mehmet BEDİR Prof. Dr. Faheem Shahzad BALOCH	*Sivas University of Science and Technology, Türkiye* *Mersin University, Türkiye*	**THE POTENTIAL OF ANATOLIAN WHEAT LANDRACES IN LOW-INPUT AGRICULTURAL SYSTEMS**
Merve YILDIZ Assoc. Prof. Dr. Asuman KAPLAN EVLİCE	*Sivas University of Science and Technology, Türkiye*	**RESEARCH ON SITOPHILUS ORYZAE IN WHEAT: A BIBLIOMETRIC ANALYSIS OF SCIENTIFIC OUTPUT, THEMATIC TRENDS, AND COLLABORATION NETWORKS**
Assoc. Prof. Dr. Asuman KAPLAN EVLİCE	*Sivas University of Science and Technology, Türkiye*	**FIVE DECADES OF PASTA RESEARCH: A BIBLIOMETRIC PERSPECTIVE**

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VENUE
Sivas University of Science and Technology

DATE
25 September 2026

TIME: 14:00-16:00

HEAD OF SESSION: Prof. Dr. Ramazan KATIRCI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Eren YİĞİTOĞLU	*National Defence University, Atatürk Strategic Research and Graduate Education Institute (ATASAREN), Türkiye*	**POLAND UNDER THE SHADOW OF PRUSSIAN HERITAGE AND NATIONAL SOCIALISM: FROM THE REVANCHISM OF VERSAILLES TO THE DANZIG CRISIS**
Asst. Prof. Dr. Tülay DAĞOĞLU AKTEMUR	*Independent Researcher, Türkiye*	**THE EPISTEMIC NEAR-MISS AND GOTHIC INTUITION IN FEMALE KNOWLEDGE IN "CHRISTABEL" AND NORTHANGER ABBEY**
Assoc. Prof. Dr. Filiz DEMİR	*Karamanoğlu Mehmetbey University, Türkiye*	**HIGH-HEELED OR FLAT? EXAMINING WOMEN MANAGERS' FOOTWEAR CHOICES IN THE CONTEXT OF AUTHORITY, POWER, AND PROFESSIONAL IDENTITY**
Sıla COŞKUN Assoc. Prof. Dr. Ülkü Mazman İTİK	*Sivas Cumhuriyet University, Türkiye*	**ARTIFICIAL INTELLIGENCE TRANSFORMATION IN ACCOUNTING RECORDS: DETECTION OF SEMANTIC–ACCOUNTING INCONSISTENCIES IN TURKISH E-DOCUMENTS USING EXPLAINABLE ARTIFICIAL INTELLIGENCE**
Prof. Dr. Ramazan KATIRCI Prof. Dr. Metin ZONTUL Res. Asst. Nusret GÖN	*Sivas University of Science and Technology, Türkiye*	**MULTILINGUAL SPEECH EMOTION RECOGNITION: AN XLS-R-BASED APPROACH COMBINING TURKISH, POLISH, AND URDU CORPORA**
Prof. Dr. Ramazan KATIRCI Prof. Dr. Metin ZONTUL Res. Asst. Nusret GÖN	*Sivas University of Science and Technology, Türkiye*	**ACCURACY IS NOT ENOUGH: AN EFFICIENCY-AWARE COMPARISON OF CNN ARCHITECTURES FOR GAN-GENERATED FACE DETECTION**
Yağmur DEĞERLİ Murat BELEN	*Ermenek District Directorate of National Education, Türkiye*	**THE ROLE OF STORYTELLING IN DESTINATION BRANDING: THE CASE OF ERMENEK**
Prof. Dr. Üzeyir OK Esra GÜN Ayşe ÇETİN Gülizar DOĞAN Elif UYSAL İlayda Deniz TUĞ Özlem ÇOBAN	*Bolu Abant İzzet Baysal University, Türkiye*	**LOST WHILE SCROLLING: DEVELOPMENT AND VALIDATION OF A MULTIDIMENSIONAL DIGITAL ADDICTION SCALE AND ITS ASSOCIATIONS WITH MENTAL HEALTH**

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VENUE
Sivas University of Science and Technology

DATE
25 September 2026

TIME: 14:00-16:00

HEAD OF SESSION: Res. Asst. Dr. Muhammed TATAR

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Asst. Prof. Dr. Amjad ALİ Res. Asst. Dr. Muhammed TATAR Assoc. Prof. Dr. Fatih ÖLMEZ	*Sivas University of Science and Technology, Türkiye*	**BIOGENIC NANOPARTICLES FOR MANAGING PLANT DNA VIRUSES AND THEIR INSECT VECTORS**
Res. Asst. Dr. Muhammed TATAR Asst. Prof. Dr. Amjad ALİ Assoc. Prof. Dr. Fatih ÖLMEZ	*Sivas University of Science and Technology, Türkiye*	**THE RHIZOSPHERE MICROBIOME AS A BIOLOGICAL SHIELD AGAINST PLANT DISEASES**
Res. Asst. Dr. Muhammed TATAR Asst. Prof. Dr. Amjad ALİ	*Sivas University of Science and Technology, Türkiye*	**OPTIMIZATION OF IPBS RETROTRANSPOSON MARKERS FOR MOLECULAR CHARACTERIZATION AND GENETIC DIVERSITY ASSESSMENT OF PENICILLIUM EXPANSUM ISOLATES**
Asst. Prof. Dr. Amjad ALİ Res. Asst. Dr. Muhammed TATAR	*Sivas University of Science and Technology, Türkiye*	**IDENTIFICATION OF INFORMATIVE SCOT MARKERS FOR GENETIC DIVERSITY ANALYSIS OF PENICILLIUM EXPANSUM ISOLATES**
Ferhat YÖRÜK Assoc. Prof. Dr. İbrahim YEMEZ	*Sivas Cumhuriyet University, Türkiye*	**DETERMINING THE FACTORS INFLUENCING THE USE OF ARTIFICIAL INTELLIGENCE: AN APPLICATION**
Sarmad Ali QURESHI Prof. Dr. Kağan KÖKTEN Assoc. Prof. Dr. Muhammad Azhar NADEEM	*Sivas University of Science and Technology, Türkiye*	**INTERMEDIATE WHEATGRASS (THINOPYRUM INTERMEDIUM) AS A MODEL FOR INNOVATION IN PERENNIAL GRAIN BREEDING: FROM CONVENTIONAL SELECTION TO GENOMICS-ASSISTED AND MACHINE LEARNING APPROACHES**
Res. Asst. Dr. Meliha Feryal SARIKAYA Assoc. Prof. Dr. Muhammad Azhar NADEEM	*Sivas University of Science and Technology, Türkiye*	**ARTIFICIAL INTELLIGENCE AND HIGH-THROUGHPUT PHENOTYPING IN FORAGE CROP BREEDING**
Res. Asst. Dr. Meliha Feryal SARIKAYA Assoc. Prof. Dr. Muhammad Azhar NADEEM	*Sivas University of Science and Technology, Türkiye*	**FROM REFERENCE GENOMES TO PANGENOMES NEXT-GENERATION APPROACHES FOR GENETIC DIVERSITY ANALYSİS IN FORAGE CROPS**

ONLINE SESSIONS

DATE: 26.09.2026

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DATE
26 September 2026

TIME
10:00 – 12:00

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862 1528 3413 | 123456

HEAD OF SESSION: Asst. Prof. Dr. Rıdvan UÇAR

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Agr. Eng. Muhammed Emin EROL Prof. Dr. Ercan CEYHAN	*Selcuk University, Türkiye*	**GERMINATION RESPONSES OF ALFALFA CULTIVARS TO SEED COATING, STORAGE AND TRANSFER CONDITIONS**
Agr. Eng. Hamza DOĞAN Prof. Dr. Ercan CEYHAN	*Selcuk University, Türkiye*	**RESPONSE OF GERMINATION PERFORMANCE TO SEED COATING, STORAGE, AND TRANSPORTATION IN SUGAR BEET CULTIVARS**
Agr. Eng. Hamza DOĞAN Prof. Dr. Ercan CEYHAN	*Selcuk University, Türkiye*	**EFFECTS OF COATING, STORAGE AND TRANSPORTATION ON EARLY SEEDLING GROWTH IN SUGAR BEET CULTIVARS**
Agr. Eng. Muhammed Emin EROL Prof. Dr. Ercan CEYHAN	*Selcuk University, Türkiye*	**EFFECTS OF SEED COATING, STORAGE AND TRANSFER PROCESSES ON EARLY SEEDLING DEVELOPMENT AND BIOMASS ACCUMULATION IN DIFFERENT ALFALFA CULTIVARS**
Asst. Prof. Dr. Selim ÖZDEMİR Prof. Dr. Erdal ÇAÇAN	*Bingöl University, Türkiye*	**EFFECTS OF BIOSTIMULANT-ASSISTED SEED PRIMING ON GERMINATION AND EARLY SEEDLING DEVELOPMENT IN FIELD CROPS UNDER DROUGHT STRESS**
Asst. Prof. Dr. Rıdvan UÇAR	*Pamukkale University, Türkiye*	**CAPER (CAPPARIS SPINOSA L.): BOTANICAL CHARACTERISTICS, PHYTOCHEMICAL COMPOSITION, PHARMACOLOGICAL EFFECTS, AND POTENTIAL FOR USE AS A BEE PASTURE**
Asst. Prof. Dr. Rıdvan UÇAR	*Pamukkale University, Türkiye*	**AGRICULTURAL IMPORTANCE OF MAIZE (ZEA MAYS L.), POLLEN POTENTIAL, AND EVALUATION POTENTIAL AS A BEE PASTURE**
Esra TOKGÖZ Res. Asst. Zeynep YUMLU Assoc. Prof. Dr. Mustafa AKBABA Assoc. Prof. Dr. Emre EVLİCE	*Sivas University of Science and Technology, Türkiye*	**CROPPING PATTERN OF IRRIGATED AGRICULTURE, INDUSTRIAL AND FORAGE CROPS IN SIVAS PROVINCE**

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DATE
26 September 2026

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HEAD OF SESSION: Asst. Prof. Dr. Oğuzkağan ALIÇ

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Asst. Prof. Dr. Oğuzkağan ALIÇ	*Eskişehir Technical University, Türkiye*	**MULTI-OBJECTIVE OPTIMIZATION OF PHOTOVOLTAIC SYSTEM ORIENTATION CONSIDERING ADJUSTMENT EFFORT INDEX**
Res. Asst. Şuanur KABA GEZER Assoc. Prof. Ekin ASLAN Assoc. Prof. Erdem ASLAN	*Kırşehir Ahi Evran University, Türkiye* *Kayseri University, Türkiye* *Erciyes University, Türkiye*	**NUMERICAL INVESTIGATION OF FOCAL-LENGTH SCALING IN GAP METALENSES AT 850 NM**
Asst. Prof. Dr. Mücahit SOYASLAN	*Sakarya University of Applied Sciences, Türkiye*	**A MEASUREMENT AND INSPECTION SYSTEM FOR REMOTE DETECTION OF HEADLAMP ALIGNMENT AND LIGHTING CHARACTERISTICS OF MOVING VEHICLES**
Feride Özlem GÜRGEZ Alperen ÇELİK	*Beta Enerji ve Teknoloji A.Ş., Türkiye*	**DESIGN, MANUFACTURING, AND TESTING OF A CORRUGATED-WALL TRANSFORMER WITH A CONVENTIONAL OIL-TYPE ON-LOAD TAP CHANGER**
Fatma Hira ŞAHİNKAYA Res. Asst. Hüseyin Saygın PORTAKAL	*Izmir Katip Celebi University, Türkiye* *Izmir University of Economics, Türkiye*	**IDENTIFICATION OF POTENTIAL PTP1B INHIBITORS IN TYPE 2 DIABETES BY PHARMACOPHORE-BASED VIRTUAL SCREENING**
Asst. Prof. Dr. S. Mert ÖZER	*Eskişehir Technical University, Türkiye*	**HYBRID OPTIMIZATION-BASED PID DESIGN FOR AUTOMATIC VOLTAGE REGULATOR SYSTEMS**
Asst. Prof. Dr. Erdem DİLMEN	*Pamukkale University, Türkiye*	**ANN BASED GENERALIZED PREDICTIVE CONTROL OF A DC MOTOR UNDER DISTURBANCE**

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HEAD OF SESSION: Assoc. Prof. Dr. Yasemin AKGÜN

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Assoc. Prof. Dr. Yasemin AKGÜN Mahmut Esat AYYILDIZ	*Ordu University, Türkiye*	**FIRE RESISTANCE OF MICRO-CONCRETES PRODUCED WITH CALCINED MARL-BLENDED CEMENTS**
Asst. Prof. Dr. Mehmet BAKIRCI	*Karabuk University, Türkiye*	**A PHYSICS-CONSTRAINED REDUCED-ORDER FRAMEWORK FOR TAFONI-INSPIRED GRADED GYROID TPMS TURBINE-BLADE COOLING: MORPHOLOGY MAPPING, LITERATURE BENCHMARKING, AND ROBUST DESIGN SCREENING**
Asst. Prof. Dr. Mehmet BAKIRCI	*Karabuk University, Türkiye*	**RARE-EARTH-DOPED YSZ SMART OPTICAL SENSOR COATINGS FOR GAS TURBINE AND JET ENGINE TURBINE BLADES: A LITERATURE-VALIDATED, VALIDATION-GATED MULTI-CRITERIA FRAMEWORK FOR TEMPERATURE AND STRUCTURAL HEALTH MONITORING POTENTIAL**
Murat AŞICI Assoc. Prof. Dr. Kaan TÜRKER	*Murat Asıcı Engineering, Türkiye* *Balıkesir University, Türkiye*	**EFFECTIVENESS OF FLUID VISCOUS DAMPERS IN PREVENTING SOFT-STORY COLLAPSE UNDER NEAR-FAULT AND FAR-FAULT GROUND MOTIONS: A PERFORMANCE-BASED ASSESSMENT**
Asst. Prof. Dr. Hakan YURTKURAN	*Yozgat Bozok University, Türkiye*	**DIGITAL PRODUCT PASSPORTS AND CARBON TRACEABILITY IN MACHINING: A CONTEMPORARY REVIEW FOR SUSTAINABLE MANUFACTURING**
Asst. Prof. Dr. Çağrıalp ARSLAN Assoc. Prof. Dr. Ümit TAYFUN	*Bartın University, Türkiye*	**PERFORMANCE ENHANCEMENTS OF COCONUT FIBER-REINFORCED POLYLACTIC ACID COMPOSITES VIA APPLICATION OF TREATMENTS FOR FIBER SURFACE**
Giray Raif BALTA Utku ŞENTÜRK	*Ege University, Türkiye*	**NUMERICAL ANALYSIS OF A COMMERCIAL 10X7E DRONE PROPELLER: VALIDATION AND INVESTIGATION**

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HEAD OF SESSION: Prof. Milena APOSTOLOVSKA STEPANOSKA

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Ekawati EKAWATI Isnawati ISNAWATI Sarikun SARIKUN	*University of 17 Agustus 1945 Samarinda, Indonesia*	**THE PARADIGM SHIFT IN QUALITY ASSURANCE IN INDONESIAN HIGHER EDUCATION: AN ANALYSIS OF THE LEGAL GAPS IN THE TRANSITION TO MINISTERIAL REGULATION NO. 39 OF 2025 AND STRATEGIES FOR IMPLEMENTING QUALITY ASSURANCE**
Abdul ROKHIM Kamaludin KAMALUDIN Sarikun SARIKUN	*University of 17 Agustus 1945 Samarinda, Indonesia*	**A LEGAL REVIEW OF UNDERAGE MARRIAGES AND DIVORCES AT THE CLASS IA RELIGIOUS COURT IN SAMARINDA**
Dr. Mariana VATAMANITA	*Constantin Stere University of European Political and Economic Studies, Republic of Moldova*	**CRIMINAL LIABILITY OF PUBLIC OFFICIALS IN THE ISSUANCE OF CONSTRUCTION PERMITS IN THE REPUBLIC OF MOLDOVA: ABUSE OF OFFICE, NEGLIGENCE AND THE IMPACT OF ADMINISTRATIVE DECISIONS**
Hoang Le BUU	*Thu Dau Mot University, Vietnam*	**SUBSTANTIVE GENDER EQUALITY THROUGH THE LENS OF FEMINIST LEGAL THEORY: IMPLICATIONS FOR REFORMING VIETNAMESE LAW**
Advocate Abhinav MISHRA Saumya SINGH Neha BERMA	*Allahabad High Court, India* *Deen Dayal Upadhyaya Gorakhpur University, India* *Central University of South Bihar, India*	**SHARED COGNITIVE INFLUENCE AND UNSANCTIONED TRIAL: IMPLICATIONS FOR HUMAN RIGHTS, CORPORATE REPUTATION AND ECONOMIC GOVERNANCE**
Neha BERMA Anjali KUMARI Asst. Prof. Dr. Poonam KUMARI	*Central University of South Bihar, India*	**SOVEREIGNTY, SEA, AND SUSTAINABILITY: AN ENVIRON-LEGAL STUDY OF MARINE GOVERNANCE IN THE INDIAN OCEAN**
Sarikun SARIKUN	*University of 17 Agustus 1945 Samarinda, Indonesia*	**ASPECTS OF LEGAL CERTAINTY IN THE TAX REPORTING SYSTEM IN INDONESIA**
Sarkowi V ZAHRY Isnawati ISNAWATI Lisa Astria MILASARI	*University of 17 Agustus 1945 Samarinda, Indonesia*	**INCREASING PUBLIC PARTICIPATION IN THE IMPLEMENTATION OF LOCAL GOVERNMENT THROUGH THE LOCAL DEMOCRACY STRENGTHENING PROGRAM**
Prof. Milena APOSTOLOVSKA STEPANOSKA Prof. Hristina RUNCHEVA TASEV Prof. Vasko NAUMOVSKI	*Ss. Cyril and Methodius University in Skopje, North Macedonia*	**INTELLECTUAL PROPERTY GOVERNANCE AND ARTIFICIAL INTELLIGENCE IN A CANDIDATE COUNTRY: LEGAL FRAGMENTATION, REGULATORY GAPS AND EU-ORIENTED POLICY RESPONSES**
Faraja James NDAALIO Asst. Prof. Dr. Saurabh KISHOR	*Sharda University, India*	**FROM, YOUTH MIND**

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HEAD OF SESSION: Assoc. Prof. Sameer Babu M

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Andi INDRAWATI Nurfitriani NURFITRIANI Fatimah ASYARI	*University of 17 Agustus 1945 Samarinda, Indonesia*	**DEVELOPMENT OF AUDIT INSTRUMENTS BASED ON STUDENT EXPECTATIONS AND INDUSTRY RELEVANCE IN THE DIGITAL ERA**
Danna SOLIHIN Patryano Gusti ANGGARA Aulya RAHMA Fadeli Yusuf AFIF	*University of Palangkaraya, Indonesia*	**A STRATEGY FOR TRANSFORMING GRADUATE QUALITY AUDITS THROUGH THE INTEGRATION OF CAREER PATH READINESS INDICATORS INTO HIGHER EDUCATION QUALITY ASSURANCE**
Eka YUDHYANI Andi INDRAWATI Nurfitriani NURFITRIANI	*University of 17 Agustus 1945 Samarinda, Indonesia*	**A COMPARATIVE ANALYSIS OF AMI RESULTS IN RELATION TO THE PROSPECTS FOR ACHIEVING 'EXCELLENT' ACCREDITATION AT LAMEMBA**
Sayid IRWAN George Louis David LENTO	*University of 17 Agustus 1945 Samarinda, Indonesia*	**ANALISIS STRATEGI PENGEMBANGAN PERGURUAN TINGGI SWASTA DI SAMARINDA DALAM MENGHADAPI PEMINDAHAN IBU KOTA NUSANTARA**
Evi Kurniasari PURWANINGRUM	*University of 17 Agustus 1945 Samarinda, Indonesia*	**GAP ANALYSIS AND RECOMMENDATIONS FOR IMPROVING THE QUALITY OF HIGHER EDUCATION**
Ekawati EKAWATI Sarikun SARIKUN	*University of 17 Agustus 1945 Samarinda, Indonesia*	**QUALITY ASSURANCE IN HIGHER EDUCATION BASED ON THE P.D.C.A CYCLE**
Mohd Shahbaz KHAN Assoc. Prof. Sameer Babu M	*Jamia Millia Islamia, India*	**DIGITAL BEHAVIOUR AND ONLINE VERBAL AGGRESSION: EDUCATIONAL PERSPECTIVES FOR SAFER ONLINE COMMUNITIES**
Liubov ALTHAIM	*Ternopil Volodymyr Hnatiuk National Pedagogical University, Ukraine*	**PSYCHOLOGICAL AND PEDAGOGICAL FEATURES OF THE EFFECTIVENESS OF DISTANCE LEARNING**
Dr. Aliyu Abdulkadir MUHAMMAD Abbas Muhammad LABBO Dr. Hauwa Muhammad ALIYU	*Aminu Kano College of Islamic and Legal Studies, Nigeria*	**ITEM ANALYSIS AS A MEANS OF IMPROVING THE QUALITY OF MULTIPLE-CHOICE QUESTIONS**
Sumarni SUMARNI Ahmad JUBAIDI Atika Rea DIANA	*University of 17 Agustus 1945 Samarinda, Indonesia*	**A STUDY ON THE SDGS POLICY OF INCLUSIVE EDUCATION FOR PEOPLE WITH DISABILITIES IN SAMARINDA CITY**

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HEAD OF SESSION: Dr. Zineb SEKKOUT

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Roguai SABRINA	*Abbes Laghrour University, Algeria*	**ENHANCED PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE USING CUO NANOPARTICLES**
Akram HOSSEINIAN	*University of Tehran, Iran*	**ADSORBING & DESTRUCTURING THE TABUN BY C20 FULLERENE**
Touran MOHAMMADI Habib RAZMI Leila DOLATYARI Mohamad Reza YAFTIAN	*Azarbaijan Shahid Madani University, Iran* *Islamic Azad University, Iran* *University of Zanjan, Iran*	**CHROMIUM(VI) REMOVAL FROM WATER SOLUTIONS USING POLYVINYL CHLORIDE BASED ELECTROSPUN NANOFIBER DISK CONTAINING A DEEP EUTECTIC SOLVENT**
Fatemeh NAJAFI Leila DOLATYARI Hassan SHAYANI-JAM Mohammad Reza YAFTIAN	*University of Zanjan, Iran* *Islamic Azad University, Iran*	**APPLICATION OF THE IONIC LIQUID CYPHOS® IL101 EXTRACTANT FOR THE SOLVENT EXTRACTION/SEPARATION OF HEAVY METALS**
Ashima DHIMAN Assoc. Prof. Dr. Sameer Babu M	*Jamia Millia Islamia, India*	**GENERATIVE ARTIFICIAL INTELLIGENCE IN CHEMISTRY EDUCATION: A BIBLIOMETRIC ANALYSIS OF RESEARCH TRENDS, EMERGING THEMES, AND FUTURE DIRECTIONS**
Zohreh DOUSTI Hassan SHAYANI-JAM Farhad KABIRI ESFAHANI Mohammad Reza YAFTIAN	*The University of Zanjan, Iran*	**SPECTROPHOTOMETRIC DETERMINATION OF Cr(VI) AFTER SOLID-PHASE EXTRACTION-PRECONCENTRATION USING IONIC LIQUID-CONTAINING POLYMERIC ELECTROSPUN NANOFIBERS**
Said KERRAJ Mohamed ELMAMOUNI Mohamed MOUSSAOUI	*Hassan II University of Casablanca, Morocco* *Mohammed VI Polytechnic University, Morocco*	**TUNING THE ELECTRONIC AND OPTICAL PROPERTIES OF RUTHENIUM SENSITIZERS FOR DYE-SENSITIZED SOLAR CELLS**
Dr. Zineb SEKKOUT Omaima BOUDAIA	*Hassan II University of Casablanca, Morocco*	**FLAVONOID-MEDIATED SUPPRESSION OF LYMPHOCYTE RESPONSES IN SPLENOCYTES AND THYMOCYTES**
S. Ramya PRIYA M. THENMOZHI	*Vels Institute of Science, Technology and Advanced Studies, India*	**PRELIMINARY PHYTOCHEMICAL SCREENING OF METHANOLIC EXTRACT OF FRESH FLOWERS OF BARLERIA CRISTATA**
Fatemeh CHABAHARI Faezeh ZAREI Leila DOLATYARI Mohammad Reza YAFTIAN	*The University of Zanjan, Iran*	**STUDY AND OPTIMIZATION OF LEACHING OF Cr(VI)-CONTAMINATED SOILS WITHOUT POTENTIAL INTERFERENCE FROM Cr(III) OXIDATION**

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DATE
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HEAD OF SESSION: Dr. İlhan DANACI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Dr. Mesut NAMLI Dr. Burak KILIÇ Özgür GÜRBÜZOĞLU Assoc. Prof. Dr. Mehmet DEMİRALAY	*Artvin Coruh University, Türkiye* *Ministry of Agriculture and Forestry, Türkiye*	**COMPARATIVE EVALUATION OF THE PHYSICOCHEMICAL PROPERTIES OF HONEY SAMPLES FROM DIFFERENT GEOGRAPHICAL ORIGINS**
Dr. Hikmet YONAT	*Ordu University, Türkiye*	**SPREAD AND HOST STATUS OF THE PLANT PARASITE Viscum album L. IN HAZELNUT ORCHARDS IN ORDU AND GİRESUN**
Asst. Prof. Dr. Elmas ULUTAŞ	*Yozgat Bozok University, Türkiye*	**COMPARISON OF ROUTINE HEMATOLOGICAL PARAMETERS AND HEMATOLOGICAL INFLAMMATORY INDICES IN PAIRED BLOOD SAMPLES COLLECTED IN K2EDTA AND LITHIUM HEPARIN TUBES FROM HEALTHY RATS**
Besime DOĞAN DAŞ Aydın DAŞ	*Harran University, Türkiye*	**EVALUATION OF SOME FEED ADDITIVES USED IN CAT-DOG NUTRITION FROM THE PERSPECTIVE OF ANIMAL HUSBANDRY**
Esra TOKGÖZ Res. Asst. Zeynep YUMLU Assoc. Prof. Dr. Mustafa AKBABA Assoc. Prof. Dr. Emre EVLİCE	*Sivas University of Science and Technology, Türkiye*	**GENERAL ASSESSMENT OF THE CROPPING PATTERN IN DRY FARMING AREAS OF SIVAS PROVINCE**
Res. Asst. Zeynep YUMLU Dr. Gamze ERDURMUŞ Dr. Abdullah YILMAZ Assoc. Prof. Dr. Emre EVLİCE	*Sivas University of Science and Technology, Türkiye* *Plant Protection Central Research Institute, Türkiye*	**IN VITRO NEMATICIDAL EFFICACY OF THYME AND LAVENDER ESSENTIAL OILS IN AN OIL-IN-WATER EMULSION (EW) FORMULATION AGAINST MELOIDOGYNE INCOGNITA**
Prof. Dr. Kağan KÖKTEN Ayşe TAŞKIN	*Sivas University of Science and Technology, Türkiye*	**MOLECULAR MARKER STUDIES CONDUCTED TO DETERMINE THE GENETIC DIVERSITY OF FENUGREEK**
Prof. Dr. Kağan KÖKTEN Ayşe TAŞKIN	*Sivas University of Science and Technology, Türkiye*	**THE IMPORTANCE, USAGE AREAS, AND QUALITY CRITERIA OF LEGUME AND GRASS FORAGE CROPS IN TURKISH AGRICULTURE**

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HEAD OF SESSION: Asst. Prof. Dr. Gül GÜN

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Asst. Prof. Dr. Ayşegül Ladin SÜMER	*Aydın Adnan Menderes University, Türkiye*	**THE IMPACT OF CBRT POLICY RATE CYCLES AFTER THE 2008 GLOBAL CRISIS ON THE REAL AND FINANCIAL SECTORS: IMPULSE-RESPONSE ANALYSIS**
Asst. Prof. Dr. Gül GÜN	*Munzur University, Türkiye*	**BIBLIOMETRIC ANALYSIS OF THE CONCEPT OF DIGITAL LEADERSHIP USING R STUDIO**
Asst. Prof. Dr. Gül GÜN	*Munzur University, Türkiye*	**ANALYSIS OF MACHINE LEARNING IN BUSINESSES USING THE R PROGRAM**
Asst. Prof. Dr. Selman TEMİZ Lect. Alperen Timuçin SÖNMEZ	*Yozgat Bozok University, Türkiye*	**FROM HIGH-TECH TO HIGH-TOUCH: ANALYZING THE ADVERTISING MESSAGES OF LEADING BANKS IN TURKIYE FROM AN H2H MARKETING PERSPECTIVE**
Assoc. Prof. Dr. Selçuk Yasin YILDIZ	*Sivas Cumhuriyet University, Türkiye*	**SCHADENFREUDE GENERATION IN THE CONTEXT OF DIGITAL LYNCH CULTURE AND BRAND CRISES**
Assoc. Prof. Dr. Selçuk Yasin YILDIZ	*Sivas Cumhuriyet University, Türkiye*	**SOCIAL COMMERCE BEHAVIORS OF SILVER ECONOMY CONSUMERS IN THE CONTEXT OF INFORMATION ASYMMETRY AND RISK PERCEPTION**
Prof. Dr. Ferhat PEHLİVANOĞLU Zeynep GÜRBÜZ	*Kocaeli University, Türkiye*	**AGRICULTURAL PRODUCTION EFFICIENCY BY PROVINCE IN TURKEY**
Res. Asst. Dr. Mustafa YAPAR Asst. Prof. Dr. Burcu KUZUCU YAPAR	*Recep Tayyip Erdogan University, Türkiye*	**THE IMPACT OF SOCIODEMOGRAPHIC FACTORS ON THE DEVELOPMENT OF ELECTRONIC COMMERCE**
Hazal TUNA Dr. Gülnaz KILIÇ ÖZKAYNAR	*Sivas Cumhuriyet University, Türkiye* *TÜRASAŞ General Directorate, Türkiye*	**OTHERING IN THE WORKPLACE: A COMPARATIVE ANALYSIS OF SYRIAN MIGRANT WORKERS IN TÜRKİYE AND TURKISH MIGRANT WORKERS IN GERMANY, AND A PROPOSED MODEL**

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HEAD OF SESSION: Asst. Prof. Dr. Barış KANTOĞLU

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Merve GÜLER Prof. Dr. Nuri Murat YAĞMURLU	*İnönü University, Türkiye*	**NUMERICAL APPROXIMATION USING A COLLOCATION SCHEME WITH QUINTIC HERMITE BASIS FUNCTIONS**
Abdulrahman ELHİSSO Assoc. Prof. Dr. Mehmet KÖKÜM Assoc. Prof. Dr. Mustafa KANIK Asst. Prof. Dr. Musa BALKAYA Asst. Prof. Dr. Aynur DİKBAŞ	*Fırat University, Türkiye* *Kahramanmaraş Sütçü İmam University, Türkiye* *Istanbul University-Cerrahpaşa, Türkiye*	**PALEOSEISMOLOGICAL EVIDENCE FOR HOLOCENE SURFACE RUPTURING ALONG THE KAVAKBAŞI FAULT ZONE**
Asst. Prof. Dr. Uras PANAHI	*Artvin Çoruh University, Türkiye*	**PROTOCOL PERFORMANCE ANALYSIS OF ADAPTIVE DUTY-CYCLING MECHANISMS IN WIRELESS SENSOR NETWORKS**
Asst. Prof. Dr. Barış KANTOĞLU	*Düzce University, Türkiye*	**DIGITALIZATION AND SUSTAINABILITY IN FOOD COLD CHAIN LOGISTICS: A BIBLIOMETRIC AND THEMATIC ANALYSIS**
Ayşe Sude ÖZDEN Ali Rıza OCAK Assoc. Prof. Dr. Negin MELEK	*Giresun University, Türkiye* *Gümüşhane University, Türkiye*	**ADAPTIVE TRAFFIC SIGNAL SYSTEM AT TRAFFIC LIGHT CONTROLLED INTERSECTIONS**
Nejla GENÇ Asst. Prof. Dr. Halil İbrahim EĞİLMEZ	*Hitit University, Türkiye*	**MATHEMATICAL MODELING OF THE BLACK SEA ANCHOVY-PLANKTON SYSTEM: EQUILIBRIUM AND STABILITY ANALYSIS**
Nilay ÖZÇELİK Asst. Prof. Dr. Umut SARAY	*Sivas Cumhuriyet University, Türkiye*	**INCREMENTAL DISCRIMINATORY VALUE OF SOCIOECONOMIC AND HEALTHCARE-ACCESS INFORMATION FOR DOCUMENTED IRON-CHELATION ADHERENCE IN THALASSEMIA**
Lect. Dr. Adnan GÖKTEN Asst. Prof. Dr. Hasan Beytullah DÖNMEZ Asst. Prof. Dr. Erkut TEKELİ	*Çukurova University, Türkiye* *Muğla Sıtkı Koçman University, Türkiye*	**A QUANTITATIVE ASSESSMENT OF TRAINING-DATA SCARCITY, IMAGE CORRUPTIONS AND ACQUISITION-ENVIRONMENT DIFFERENCE IN RICE LEAF DISEASE CLASSIFICATION WITH CONVNEXT-TINY**

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HEAD OF SESSION: Asst. Prof. Dr. Jasneet KAUR

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Aayesha FARHIN	*MMAJ Academy of International Studies, Jamia Millia Islamia, India*	**ARTIFICIAL BORDERS AND FRAGMENTED NATIONS: COLONIAL STATE-MAKING AND IDENTITY POLITICS IN THE LEVANT**
Nesar Hussain MOHAMMADI Ali Sina MOHAMMADI Sayed Ali Reza BALKHI Shah Wali REZAIE	*Haidr Boys High School, Afghanistan*	**HUMAN RIGHTS AND FOREIGN POLICY: BALANCING NATIONAL INTERESTS AND INTERNATIONAL HUMAN RIGHTS NORMS**
Mustapha GONI Dr. Babagana MOHAMMED Hamza Umar ABORE	*Kashim Ibrahim University, Nigeria* *University of Maiduguri, Nigeria*	**POST-CONFLICT RESETTLEMENT PROGRAMME AND SOCIO-ECONOMIC DEVELOPMENT IN BAMA LOCAL GOVERNMENT AREA, BORNO STATE, NIGERIA**
Asst. Prof. Dr. Jasneet KAUR Jhyestha Meha SINGAL Prakhar DIKSHIT Tanmay MADESHIA	*University of Delhi, India*	**SHARED WATERS, DIVERGENT RULES: SRI LANKA, THE UAE, AND THE GOVERNANCE OF PRIVATE MARITIME SECURITY INFRASTRUCTURE IN THE INDIAN OCEAN**
Nasir Abba YUSUF	*Kampala International University, Uganda*	**PROMISES UNKEPT: JIMMY CARTER, THE ANTI-APARTHEID MOVEMENT, AND THE GAP BETWEEN HUMAN RIGHTS RHETORIC AND ACTION**
Dr. Ayobami Oluwasegun ADIGUN	*Federal University Oye-Ekiti, Nigeria*	**FEMALE BEAUTY AND SPIRITUALITY IN CONTEMPORARY SOCIETY: A PHILOSOPHICAL ANALYSIS OF THEIR SIGNIFICANCE FOR FAMILY LIFE**
Erisela MARKO Dr. Blegina HASKO BEZO	*European University of Tirana, Albania*	**ADVERTISING IN TRADITIONAL AND SOCIAL MEDIA: AUDIENCE PERCEPTIONS OF INFLUENCE, CREDIBILITY, AND SOCIAL RESPONSIBILITY IN ALBANIA**
Nguyen Thi PHUONG Phan Ngoc Thiet KE	*Vinh Medical University, Vietnam* *The University of Danang, Vietnam*	**COMPARATIVE ANALYSIS OF STRENGTH AND POWER CHARACTERISTICS ACROSS PICKLEBALL, TENNIS, BADMINTON AND TABLE TENNIS**
Orlinda SINANAJ Romina SINANAJ	*University of Insurance and Finance, Bulgaria* *International University of Struga, North Macedonia*	**REAL ESTATE BROKERAGE REGULATION IN THE WESTERN BALKANS: FORMAL CONVERGENCE AND SUBSTANTIVE DIVERGENCE TOWARD EU STANDARDS FOR THE PREVENTION OF MONEY LAUNDERING**
Adeleke O. ISHOLA	*Koladaisi University, Nigeria*	**NUCLEAR WEAPONS AND INTERNATIONAL ORDER: THE PROMISE AND LIMITS OF THE NPT**

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HEAD OF SESSION: Assoc. Prof. Dr. Abdülhakim Bahadır DARI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Syeda Nada QADRI Aayesha FARHEEN	*Aligarh Muslim University, India* *Jamia Millia Islamia, India*	**FROM KONYA TO BAGHDAD: RETHINKING SUFI TRADITIONS AS TRANSREGIONAL NETWORKS OF PEACE AND SOCIAL COHESION**
Noorjan MOSSAWI Prof. Dr. Samira NASIRZADEH	*Ahlul Bayt International University, Iran*	**DEVELOPING DECISION-MAKING SKILLS IN WOMEN**
Noorjan MOSSAWI	*Ahlul Bayt International University, Iran*	**SOCIAL RESILIENCE TRAINING FOR ACTIVE WOMEN**
Asst. Prof. Dr. Violla MAKHZOUM Dr. Zeinab SLEEM Dr. Oussama DABBOUL	*Islamic University of Lebanon, Lebanon* *Al-Maaref University, Lebanon* *Lebanese University, Lebanon*	**FROM INFORMATION CONSUMERS TO CRITICAL AI CITIZENS: RETHINKING MEDIA AND EDUCATION IN THE AGE OF GENERATIVE ARTIFICIAL INTELLIGENCE**
Turaki AISHA Isah MUSA Dr. Mohammed Mohammed NDAGI Garba BLESSED	*Ibrahim Badamasi Babangida University, Nigeria* *Kaduna Polytechnic, Nigeria*	**THE EFFECT OF MOTIVATION ON PRIMARY SCHOOL TEACHERS PERFORMANCE IN RAFI LOCAL GOVERNMENT EDUCATION AUTHORITY OF NIGER STATE**
Mohammed Tajelsir Ali AWAD	*Sultan Qaboos University, Oman*	**4-WEEK STEP-BY-STEP PLANNER TO WRITE A RESEARCH ARTICLE/PAPER AS A PROFESSIONAL**
Liliana GIL DÍAZ Deneb Elí MAGAÑA MEDINA	*Juárez Autonomous University of Tabasco, Mexico*	**UNIVERSITY-INDUSTRY LINKAGE AND KNOWLEDGE TRANSFER**
Bindiya SHARMA	*Sharda University, India*	**GLOBAL CONFLICTS AND THE CRISIS OF INTERNATIONAL LAW: CHALLENGES TO HUMAN RIGHTS, PEACE AND ACCOUNTABILITY**

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HEAD OF SESSION: Assoc. Prof. Dr. Rrezarta GASHI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Mihaela SIMIONESCU	*University of Bucharest; Institute for Economic Forecasting of the Romanian Academy, Romania*	**THE NONLINEAR CONNECTION BETWEEN INFLATION ON INCOME/WEALTH INEQUALITY IN THE EUROPEAN UNION. MEDIATED EFFECTS AND MODERATED MEDIATION MODELS**
Jamiu Adeniyi YUSUF Tiffany Mehbari BEH-NUBEL	*National Institute for Legislative and Democratic Studies (NILDS), Nigeria* *Baze University, Nigeria*	**FROM ENERGY ACCESS TO PRODUCTIVITY: DOES TECHNOLOGICAL INNOVATION MATTER ACROSS SECTORS IN SUB-SAHARAN AFRICA?**
Maskan M. Ibnu ASHARI Eka Purnama ANNISA	*University of 17 Agustus 1945 Samarinda, Indonesia*	**THE ROLE OF THE DEPARTMENT OF CULTURE AND TOURISM IN INCREASING TOURIST VISITS TO THE SAMBALIUNG PALACE IN BERAU REGENCY**
Assoc. Prof. Dr. Rrezarta GASHI Asst. Prof. Dr. Hana GASHI AHMETI	*AAB College, Kosovo* *Pjeter Budi College, Kosovo*	**DIGITAL TRANSFORMATION AND WOMEN'S ENTREPRENEURIAL DEVELOPMENT IN THE WESTERN BALKANS: EVIDENCE FROM SECONDARY DATA**
Senior Lect. Taiwo AKINLO	*Adeyemi Federal University of Education, Nigeria*	**THE RELATIONSHIP BETWEEN REMITTANCES AND INSURANCE IN NIGERIA**
Dr. José Ángel PÉREZ CASTRO Dr. María Antonieta ESTAÑOL VIDRIO	*National Technological Institute of Mexico, Mexico* *Juárez Autonomous University of Tabasco, Mexico*	**APPROACH TO THE LABOR POVERTY IN THE STATE OF TABASCO, MEXICO**
Dr. José Ángel PÉREZ CASTRO Dr. María Antonieta ESTAÑOL VIDRIO	*National Technological Institute of Mexico, Mexico* *Juárez Autonomous University of Tabasco, Mexico*	**GAME THEORY AND THE OLIGOPOLY OF RETAIL STORES WAL-MART, CHEDRAUI, AND SORIANA IN VILLAHERMOSA, TABASCO**
Dr. María Antonieta ESTAÑOL VIDRIO Dr. José Ángel PÉREZ CASTRO	*Juárez Autonomous University of Tabasco, Mexico* *National Technological Institute of Mexico, Mexico*	**ECONOMIC STUDY OF THE PHARMACEUTICAL MARKET IN VILLAHERMOSA TABASCO, MEXICO**
Arlind MAZE Assoc. Prof. Bernard DOSTI	*University of Tirana, Albania*	**THE INFORMALITY PREMIUM: HOW EDUCATION SHAPES THE WILLINGNESS TO WORK INFORMALLY**
Aditi KUMARI	*Sharda University, India*	**CROSS-BORDER DIGITAL PAYMENTS AND MONETARY SOVEREIGNTY: THE EMERGING ECONOMIC ARCHITECTURE OF BRICS**

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HEAD OF SESSION: Assoc. Prof. Dr. Zeynep Görkem DOĞAROĞLU

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Assoc. Prof. Dr. Zeynep Görkem DOĞAROĞLU Prof. Dr. Yağmur UYSAL	*Mersin University, Türkiye*	**EFFECT OF HYDROGELS ENRICHED WITH BIOCAR FROM VINE PRUNING WASTE ON TOMATO (Solanum lycopersicum L.) GROWTH PERFORMANCE AND CHLOROPHYLL CONTENT**
Assoc. Prof. Dr. Zeynep Görkem DOĞAROĞLU Prof. Dr. Yağmur UYSAL	*Mersin University, Türkiye*	**THE EFFECT OF HYDROGEL MICROSPHERES ON THE GROWTH PERFORMANCE AND CHLOROPHYLL CONTENT OF PEPPER PLANTS**
Asst. Prof. Dr. Gökçe TUĞDEMİR KÖK Yusuf İslam GÜLMEZ	*Mersin University, Türkiye*	**HAZARDOUS CARGO OPERATIONS AT LIQUID BULK TERMINALS: A CASE STUDY FROM THE PERSPECTIVE OF INTERNATIONAL TRADE AND SUPPLY CHAIN CONTINUITY**
Assoc. Prof. Dr. Nil KONYALILAR	*İstanbul Topkapı University, Türkiye*	**PASSENGER VOLUME AND UNIT REVENUE FORECASTING AT THE ROUTE LEVEL USING MACHINE LEARNING: COMMERCIAL PLANNING OPTIMIZATION**
Araks EKMEKÇİOĞLU	*Yıldız Technical University, Türkiye*	**EFFECT OF UNDERWATER HULL CLEANING AND PROPELLER POLISHING ON SHIP SPEED–PROPULSION POWER PERFORMANCE: A CASE STUDY**
Asst. Prof. Dr. Ekrem DURMAZ	*Kastamonu University, Türkiye*	**INFLUENCE OF CELLULOSE NANOFIBRIL (CNF) AND CELLULOSE NANOCRYSTAL (CNC) COATINGS ON THE SURFACE WETTABILITY OF CORRUGATED CARDBOARD**
Res. Asst. Dr. Davut PEHLİVAN Asst. Prof. Dr. Fatih OKUMUŞ	*Mersin University, Türkiye*	**SOURCE-BASED ANALYSIS AND CLASSIFICATION OF PORT-RELATED EMISSIONS**
Asst. Prof. Dr. Emre İPEKÇİ	*Samsun University, Türkiye*	**THE RELATIONSHIP BETWEEN RAILWAY ELECTRIFICATION AND FREIGHT TRANSPORT VOLUME: A PANEL DATA ANALYSIS OF EUROPEAN COUNTRIES**

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HEAD OF SESSION: Assoc. Prof. Dr. Ceren ORAK

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Asst. Prof. Dr. Fizyon SÖNMEZ ERDOĞAN	*Hatay Mustafa Kemal University, Türkiye*	**THE IMPORTANCE AND SUSTAINABILITY OF WETLANDS: THE CASE OF MILLEYHA WETLAND**
Melike YILMAZ Prof. Dr. İsmet KAYA	*Çanakkale Onsekiz Mart University, Türkiye*	**SYNTHESIS AND CHARACTERIZATION OF AROMATIC DIHYDROXY COMPOUNDS CONTAINING AN IMINE BOND AND THEIR ALIPHATIC AND AROMATIC POLY(AZOMETHINE-URETHANES)**
Res. Asst. Kübra KÖŞE KAYA Assoc. Prof. Dr. Ceren ORAK Prof. Dr. Sabit HOROZ	*Sivas University of Science and Technology, Türkiye*	**EFFECT OF ANNEALING TEMPERATURE ON THE STRUCTURAL AND OPTICAL PROPERTIES OF ZnO NANOPARTICLES GREEN-SYNTHESIZED USING OKRA EXTRACT**
Res. Asst. Kübra KÖŞE KAYA Assoc. Prof. Dr. Ceren ORAK Prof. Dr. Sabit HOROZ	*Sivas University of Science and Technology, Türkiye*	**SEPIOLITE AS A SUPPORT MATERIAL IN PHOTOCATALYTIC COMPOSITE SYSTEMS**
Dr. Beyza CİFTÇİ Prof. Dr. Mahmut KAPLAN Prof. Dr. Kağan KÖKTEN Asst. Prof. Selim ÖZDEMİR	*Sivas University of Science and Technology, Türkiye*	**PLANT TISSUE CULTURE IN FORAGE CROPS: APPLICATIONS IN PROPAGATION, BREEDING AND MODERN BIOTECHNOLOGY**
Prof. Dr. Kağan KÖKTEN Asst. Prof. Selim ÖZDEMİR Dr. Beyza CİFTÇİ Prof. Dr. Mahmut KAPLAN	*Sivas University of Science and Technology, Türkiye*	**EFFECTS OF DIFFERENT SORGHUM (SORGHUM BICOLOR L.) AND ALFALFA (MEDICAGO SATIVA L.) MIXTURE RATIOS ON SILAGE FERMENTATION AND NUTRIENT PROPERTIES**
Asst. Prof. Selim ÖZDEMİR Prof. Dr. Kağan KÖKTEN Dr. Beyza CİFTÇİ Prof. Dr. Mahmut KAPLAN	*Sivas University of Science and Technology, Türkiye*	**EFFECTS OF DIFFERENT MAIZE (ZEA MAYS L.) AND SOYBEAN (GLYCINE MAX L.) MIXTURE RATIOS ON SILAGE QUALITY AND NUTRIENT CONTENT**
Res. Asst. Dr. Sevda UÇAR Prof. Dr. Neslihan DİKBAŞ Res. Asst. Şeyma ALIM	*Sivas University of Science and Technology, Türkiye*	**PRODUCTION, PARTIAL PURIFICATION, AND BIOCHEMICAL CHARACTERIZATION OF AMYLASE FROM BACILLUS SUBTILIS N28**

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HEAD OF SESSION: Assoc. Prof. Dr. Ferdi KIRAÇ

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Fatih ATEŞ Dr. Eda YILMAZ Prof. Dr. Sevinç NAMLI Asst. Prof. Dr. Deniz BEDİR Muhammet Taha ÇİFTÇİ	*Erzurum Technical University, Türkiye*	**EXAMINATION OF THE RELATIONSHIP BETWEEN GAMING ADDICTION AND MOTIVATION FOR SPORTS PARTICIPATION AMONG HIGH SCHOOL STUDENTS ACCORDING TO DEMOGRAPHIC VARIABLES**
Dr. Eda YILMAZ Nefise ÇELİK Prof. Dr. Sevinç NAMLI Res. Asst. Fatih ATEŞ	*Erzurum Technical University, Türkiye*	**EXAMINATION OF THE RELATIONSHIPS BETWEEN EYSENCK PERSONALITY TRAITS AND PSYCHOLOGICAL PERFORMANCE COMPONENTS IN ATHLETES AND THEIR DIFFERENCES ACCORDING TO DEMOGRAPHIC VARIABLES**
Asst. Prof. Dr. Orçun KEÇECİ	*Osmaniye Korkut Ata University, Türkiye*	**THE RELATIONSHIP BETWEEN FEAR OF MISSING OUT AND IN-GAME CONTENT PURCHASE MOTIVATIONS AMONG DIGITAL GAMERS**
Asst. Prof. Dr. Serkan GÖKALP	*Mersin University, Türkiye*	**PRIVATE HIGH SCHOOL TEACHERS' VIEWS ON LEAVING THEIR JOBS**
Mustafa DENİZ Assoc. Prof. Dr. Galip ÖNER	*Erciyes University, Türkiye*	**DEVELOPMENT OF THE INCLUSIVE EDUCATION TEXTBOOK ANALYSIS FORM: A DESIGN AND DEVELOPMENT RESEARCH**
Assoc. Prof. Dr. Ferdi KIRAÇ	*Niğde Ömer Halisdemir University, Türkiye*	**THE PARENTING STYLES PREDICTING IMAGES OF GOD**
Assoc. Prof. Dr. Tuba KARABEY Pınar AKGÜL	*Tokat Gaziosmanpaşa University, Türkiye* *Ondokuz Mayıs University, Türkiye*	**EVIDENCE-BASED CURRENT APPROACHES TO EMERGENCY NURSING IN CRIMEAN CONGO HEMORRHAGIC FEVER**

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HEAD OF SESSION: Prof. Dr. Mercan EFE GÜNEY

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Dr. Fadime KURTOĞLU	*İnönü University, Türkiye*	**THE FOUNTAIN OF LIFE (ÇEŞME-İ HAYVAN) IN KAYGUSUZ ABDAL'S DİVAN: LIFE, BEAUTY, AND TRUTH**
Asst. Prof. Dr. Niyazi Umut AKINCIOĞLU	*Turkish National Police Academy, Türkiye*	**FROM THE INDIVIDUAL TO SOCIAL STRUCTURE: THE HISTORICAL AND CONCEPTUAL TRANSFORMATION OF THEORIES OF CRIME**
Asst. Prof. Dr. Oğuz DÜZGÜN	*Bandırma Onyedi Eylül University, Türkiye*	**A PHILOSOPHICAL LOOK AT THE RELATIONSHIP BETWEEN EMOTIONS AND MORALITY WITHIN THE FAMILY**
Assoc. Prof. Dr. Mevlüt Sedat DÖNMEZ MA Student Mustafa MADAN	*Süleyman Demirel University, Türkiye*	**AUDIENCE PERCEPTION OF AI-GENERATED ADVERTISEMENTS: THE CASE OF THE CEM YILMAZ GOFRIK COMMERCIAL**
Prof. Dr. Mercan EFE GÜNEY Aylin TEPECİK Çağlı TORUN	*Dokuz Eylül University, Türkiye*	**SOCIAL POLICIES FOR DISADVANTAGED GROUPS IN TÜRKİYE AND THEIR SPATIAL IMPLICATIONS**
Assoc. Prof. Dr. Gökçen Kurtuluş ÖZTAŞKIN	*Pamukkale University, Türkiye*	**PERSONIFICATIONS IN THE EARLY BYZANTINE PERIOD MOSAICS OF THE OLYMPOS ANCIENT CITY**
Asst. Prof. Dr. Miray Dizem YILMAZ Selin PİROĞLU	*Düzce University, Türkiye*	**EVALUATION OF PEDIATRIC OUTPATIENT CLINICS IN TERMS OF SPATIAL QUALITY AND USER EXPERIENCE: THE CASE OF DÜZCE**
Asst. Prof. Dr. Ferhat ATİK	*Girne American University, TRNC*	**THE SEARCH FOR HUMAN RESPONSE IN THE AGE OF ARTIFICIAL INTELLIGENCE: EMOTIONAL AND ETHICAL DIMENSIONS OF SPEAKING WITH MACHINES**

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HEAD OF SESSION: Ho Dieu HUYEN

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Yusuf Ahmed TIJJANI Dr. Ibrahim Mohammed DIKKO Abubakar IDRIS	*Ahmadu Bello University, Nigeria* *Kaduna Polytechnic, Nigeria*	**STRATEGIC MANAGEMENT PRACTICES AND SERVICE DELIVERY EFFICIENCY IN NIGERIA'S PUBLIC SECTOR**
Hadi Sayed AHMAD	*Islamic University of Lebanon, Lebanon*	**FROM ARTIFICIAL INTELLIGENCE OUTPUTS TO AUDIT EVIDENCE: ASSESSING DATA RELIABILITY, OUTPUT ACCURACY, AND VERIFIABILITY IN ACCOUNTING AUDITING**
Ho Dieu HUYEN	*Vietnam Academy of Social Sciences, Vietnam*	**DIGITAL TRANSFORMATION AND ENHANCING THE RESILIENCE OF VIETNAMESE SMALL AND MEDIUM-SIZED ENTERPRISES AMID SUPPLY CHAIN DISRUPTIONS**
Umar Baba SHAABA	*Ahman Pategi University, Nigeria*	**BLOCKCHAIN TECHNOLOGY AND THE TRANSFORMATION OF FINANCIAL REPORTING AND AUDITING**
Charles GIDEON Ishiyaku BALA Mohammed Ishaq MOHAMMED	*Abubakar Tafawa Balewa University, Nigeria*	**DETERMINANTS OF SMART FACILITIES MANAGEMENT TECHNOLOGY ADOPTION AMONG PRACTITIONERS IN ABUJA, NIGERIA**
Musa SHEHU Yusniyati YUSRI Mohammad Noor Hisham B OSMAN Siti Zaidah Binti TURMIN	*Jigawa State Polytechnic; University Putra Malaysia, Nigeria* *University Putra Malaysia, Malaysia*	**THE MODERATING ROLE OF BOARD FINANCIAL EXPERTISE IN THE RELATIONSHIP BETWEEN BOARD ATTRIBUTES AND CORPORATE TAX AVOIDANCE: EVIDENCE FROM NIGERIA**
Muhammad Hildan RASEKA Titin RULIANA Zilfana ZILFANA	*University of 17 Agustus 1945 Samarinda, Indonesia*	**PREPARATION OF FINANCIAL REPORTS AT CV DEWA BASED ON MICRO, SMALL AND MEDIUM ENTERPRISES FINANCIAL ACCOUNTING STANDARDS (SAK EMKM)**
Gisheilla Dhea AVISHA Catur Kumala DEWI Faizal REZA	*University of 17 Agustus 1945 Samarinda, Indonesia*	**SWOT ANALYSIS IN DETERMINING THE SALES STRATEGY OF CAR PRODUCTS AT THE MITSUBISHI DEALER PT MAHAKAM BERLIAN SAMJAYA IN SAMARINDA CITY**
Mohammed Yunusa MUSA M. J. GAMBO Hamza USMAN	*Abubakar Tafawa Balewa University, Nigeria*	**IMPACT OF WASTE MANAGEMENT PRACTICES ON RESIDENTIAL RENTAL VALUES IN BAUCHI METROPOLIS**
C. Ashmitha CHELLAM Assoc. Prof. Dr. C. VAIRAVAN	*Academy of Maritime Education and Training Deemed to be University, India*	**DERANGEMENT OF SCALE: PLANETARY ECOCRITICISM AND ANTHROPOCENE FORM IN RICHARD POWERS'S PLAYGROUND**

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HEAD OF SESSION: Prof. Dr. Clara Stella VICARI AVERSA

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Assoc. Prof. Dr. Omer Shujat BHATTI Prof. Dr. Muhammad Asad GHUFRAN Muzaffar Aziz IQBAL Assoc. Prof. Dr. Saad MUJAHID Khubab HUSSAIN	*University of Management and Technology, Pakistan* *International Islamic University Islamabad, Pakistan*	**BEYOND ACCESSIBILITY: RETHINKING INCLUSIVE BUILT ENVIRONMENT DESIGN IN LAHORE'S PUBLIC PARKS FOR SPECIAL PERSONS**
Assoc. Prof. Dr. Omer Shujat BHATTI Prof. Dr. Muhammad Asad GHUFRAN Salwa SABIR Asst. Prof. Dr. Sadaf RAJA Zakra AHMAD	*University of Management and Technology, Pakistan* *International Islamic University Islamabad, Pakistan* *Punjab University, Pakistan* *Independent Researcher, Pakistan*	**BEYOND THE PANDEMIC: REIMAGINING THE SPIRIT OF COMMUNITY LIVING**
Behrooz KHAN	*Universitas Trunojoyo Madura, Indonesia*	**GENERATIVE AI AND SUSTAINABILITY REPORTING QUALITY: A SYSTEMATIC LITERATURE REVIEW OF DISCLOSURE QUALITY, GREENWASHING, AND HUMAN OVERSIGHT**
Muhammad Kabir DAUDA Adeyemi ADEGBENGA Ibrahim Musa SINGRY	*Abubakar Tafawa Balewa University, Nigeria*	**DIGITAL TECHNOLOGY ADOPTION BY REAL ESTATE FIRMS FOR ENHANCEMENT OF EMPLOYEE PRODUCTIVITY IN REAL ESTATE ACTIVITIES IN KADUNA, NIGERIA**
Zakia GUEZZEN Zakia HAMMOU Zouaoui SEREIR Aicha BOUSSOUFI Lahouaria ERROUANE	*University of Science and Technology of Oran, Algeria*	**VIBRATIONAL RELIABILITY OF BIO-BASED CYLINDRICAL SHALLOW SHELLS UNDER RESONANCE RISK**
Nuuridha MATIIN	*Nusantara School of Economics Nusantara Sangatta, Indonesia*	**THE EFFECT OF EARNING PER SHARE AND BOOK VALUE ON STOCK RETURN**
Asst. Lect. S. Santhosh KUMAR	*St. Joseph University in Tanzania, Tanzania*	**BIOHYDROGEN: ADVANCING SUSTAINABLE ENERGY THROUGH GREEN FUEL TECHNOLOGY**
Zakariyau GURAMA Musa SHEHU Abdulhamid SALIHU	*Gombe State University, Nigeria* *Jigawa State Polytechnic, Nigeria* *Nigeria Revenue Service, Nigeria*	**EFFECTS OF INTERNAL CONTROL ON FINANCIAL MANAGEMENT: A STUDY ON GOMBE STATE**
Prof. Dr. Clara Stella VICARI AVERSA Dr. Alessia G. QUATTRONE	*Mediterranea University of Reggio Calabria, Italy*	**THE PROMPT AS A COMPOSITIONAL DEVICE: HUMAN–AI DIALOGUE IN THE EARLY STAGES OF ARCHITECTURAL DESIGN**
Safer Nabil BELKACEM	*University of Amenokal Hadj Moussa Ag Akhamouk Tamanrasset, Algeria*	**NUMERICAL STUDY OF SOLAR CHIMNEYS' THERMAL PERFORMANCE FOR BUILDING VENTILATION**

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DATE
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HEAD OF SESSION: Assoc. Prof. Karina BACHTARZI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Dr. Iram LIAQAT	*Government College University Lahore, Pakistan*	**QUORUM SENSING CONTROLS BIOFILM FORMATION IN MARINE ISOLATES**
Hamid NADI Hicham OUHAKKI Nabila AUAJJAR Naima DOHOU Khalid YAMNI Moulay Laarbi OUAHIDI	*Ibn Tofail University, Morocco*	**INTEGRATED ASSESSMENT OF PHYSICOCHEMICAL AND BACTERIOLOGICAL GROUNDWATER QUALITY FOR DRINKING AND IRRIGATION IN THE FEIJA REGION, SOUTHEASTERN MOROCCO**
Victoria Folakemi AKINJOGUNLA	*Bayero University Kano, Nigeria*	**PLASTIC POLLUTION IN AQUATIC ECOSYSTEMS: EMERGING THREATS AND IMPLICATIONS**
Babita GUPTA	*Integral University, India*	**ADVANCING FOOD SAFETY IN ARTIFICIAL INTELLIGENCE: CURRENT PROGRESS, CHALLENGES, AND FUTURE DIRECTIONS**
Fikri MAULANA Zuhdi YAHYA Legowo KAMARUBAYANA	*University of 17 Agustus 1945 Samarinda, Indonesia*	**AN EVALUATION STUDY OF THE SURVIVAL RATE OF PLANTS ON RECLAMATED LAND IN A FORMER COAL MINE AREA**
Gianluca VISCUSI Flora SALZANO Veronica FOLLIERO Nicola MORANTE Maria del Carmen HIDALGO Hebat-Allah S. TOHAMY Giuliana GORRASI Gianluigi FRANCI Diana SANNINO	*University of Salerno, Italy* *Instituto de Ciencia de Materiales de Sevilla (ICMS), Spain* *National Research Centre, Egypt*	**BLOCKING ANTIBIOTIC POLLUTION AND BACTERIA CONTAMINATION VIA EFFICIENT PHOTOCATALYSIS USING N-CARBON DOTS DOPED NI@TIO2**
Assoc. Prof. Dr. Karina BACHTARZI Assoc. Prof. Dr. Assia ALLAOUI	*Frères Mentouri Constantine 1 University, Algeria*	**MICROBIOLOGICAL STUDY OF SOME HONEYS FROM THE CONSTANTINE REGION**
Loubna JRHAIDER Prof. Youssef NAIMI Dr. Fathalah ELWAHAB Prof. El Mostafa TACE	*Hassan II University of Casablanca, Morocco* *Ibn Tofail University, Morocco*	**NATURAL ANTIOXIDANTS AND ANTIMICROBIALS IN FUNCTIONAL FOODS: CURRENT ADVANCES AND FUTURE PERSPECTIVES**
Reza SADEGHI	*University of Tehran, Iran*	**EFFICACY OF KAOLIN IN CONTROLLING SITOPHILUS ZEAMAIS**
Dr. Assia ALLAOUI Dr. Karina BACHTARZI	*University of Constantine 1, Algeria*	**SENSORY EVALUATION AND PERCEPTION OF MILK QUALITY BY ALGERIAN CONSUMERS**
Kenza AIT ALI OUADDI Prof. Abdelkarim ZATNI Prof. Abdenbi ELYAMANI Prof. Abdelkarim MOUMEN Amina LACHGUER Fatima BOUMRIT	*Ibn Zohr University, Morocco*	**NUMERICAL OPTIMIZATION OF COUPLING MATRICES FOR PSEUDO-ELLIPTIC MICROWAVE FILTER SYNTHESIS**

ONLINE
Session-1

SESSION · HALL
Session-1 · Hall-2

DATE
27 September 2026

TIME
10:00 – 12:00

ZOOM ID · PASS
862 1528 3413 | 123456

HEAD OF SESSION: Asst. Prof. Dr. Mahvish JAVED

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Oluwanifemi Opeyemi AGOI Moses Adeolu AGOI Ayodele Elizabeth AGOI Hendri Hermawan ADINUGRAHA	*Obafemi Awolowo University, Nigeria* *Lagos State University of Education, Nigeria* *Osun State College of Technology, Nigeria* *Universitas Islam Negeri K.H. Abdurrahman Wahid Pekalongan, Indonesia*	**ENGINEERING SECURE AND SCALABLE BLOCKCHAIN-ENABLED PAYMENT SYSTEMS: SECURITY, CONSENSUS OPTIMIZATION, AND ECONOMIC ADOPTION CHALLENGES**
Boucif BEDDAD Jack-Gerard POSTAIRE	*Djillali Liabes University of Sidi-Bel-Abbes, Algeria* *University of Lille, France*	**SYSTEMATIC BENCHMARKING OF DEEP LEARNING APPROACHES FOR REMOTE SENSING IMAGE CLASSIFICATION**
Masitah INDRIANI Fenny FAJRIANI Zuhdi YAHYA Ismail ISMAIL Zikri AZHAM Tazri AMRULLAH Jumani JUMANI	*University of 17 Agustus 1945 Samarinda, Indonesia*	**EMPLOYEE WORK CULTURE AT CV. WANA KARYA SAMARINDA WITH THE IMPLEMENTATION OF OCCUPATIONAL SAFETY AND HEALTH MANAGEMENT**
Dr. Seyfaddin JAFAROV	*Nakhchivan State University, Azerbaijan*	**HYDROTHERMAL SYNTHESIS AND STRUCTURAL ANALYSIS OF CdSe; 0.5%Ho NANOCRYSTAL**
Ahmed Eliwi ALSALOUM	*University of the People, USA*	**CYBERSECURITY RISKS OF AI-GENERATED DIGITAL IDENTITIES: CHALLENGES, THREAT VECTORS, AND TRUST-AWARE VERIFICATION FRAMEWORKS**
Leila MOSTEFAOUI	*Mustapha Stambouli University of Mascara, Algeria*	**ÉVALUATION DE L'EFFICACITÉ ET DE LA SÉCURITÉ DES INHIBITEURS DU COTRANSPORTEUR SODIUM-GLUCOSE DE TYPE 2 (ISGLT2) DANS LA PRISE EN CHARGE DU SYNDROME MÉTABOLIQUE CHEZ LES PATIENTS ALGÉRIENS**
Aliyu Muhammad ZABI Farouq Abba WABI Abba HALI	*Federal Polytechnic Kaltungo, Nigeria* *Federal University of Health Sciences Azare, Nigeria* *Federal University of Kashere, Nigeria*	**THE IMPACT OF ARTIFICIAL INTELLIGENCE TECHNIQUES ON CYBERSECURITY THREAT DETECTION AND RESPONSE MECHANISMS**
Asst. Prof. Dr. Mahvish JAVED	*Khyber Girls Medical College, Pakistan*	**SACRAL HIATUS: A STUDY OF ITS ANATOMICAL VARIATIONS IN DRY SACRA**
O.O. ABEGUNRIN O.T. YEKINNI I.O. OLATOYE	*Federal College of Forestry, Nigeria* *University of Ibadan, Nigeria*	**PROCESS DOCUMENTATION OF ETHNOVETERINARY MEDICINE USED AS DIARRHOEA REMEDY IN RUMINANT FARMING IN GUINEA AND RAINFOREST AGROECOLOGICAL ZONES OF NIGERIA**

ONLINE
Session-1

SESSION · HALL
Session-1 · Hall-3

DATE
27 September 2026

TIME
10:00 – 12:00

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HEAD OF SESSION: Prof. Dr. Vinod Kumar VERMA

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Sabrina ROGUAI	*Abbes Laghrour University, Algeria*	**INFLUENCE OF NI INCORPORATION ON THE STRUCTURAL, MICROSTRUCTURAL, AND OPTICAL CHARACTERISTICS OF TIN OXIDE THIN FILMS PREPARED BY THE PSP TECHNIQUE**
Prof. Dr. Vinod Kumar VERMA Prof. Dr. Klimis NTALIANIS Prof. Dr. Chao-Tung YANG Prof. Dr. Carlos MORENO Prof. Dr. Eric GAMESS Prof. Dr. Monica Karel HUERTA Prof. Dr. Roger CLOTET Prof. Dr. Vimal Rau APAROW	*Sant Longowal Institute of Engineering and Technology, India*	**ARTIFICIAL INTELLIGENCE BASED COMPREHENSIVE EXPLORATIONS ON EMERGING TECHNOLOGIES FOR ENERGY SECTOR APPLICATIONS**
T. AARTHI Asst. Prof. Dr. M. PONMURUGAN	*Central University of Tamil Nadu, India*	**EFFICIENCY AT MAXIMUM POWER OF FINITE TIME CARNOT ENGINE USING ONE COMPONENT PLASMA AS A WORKING MEDIUM IN LOW DISSIPATION REGIME**
Faruk SANI Ismaila Garba SAIDU	*Usmanu Danfodiyo University, Nigeria*	**OPTIMIZATION OF CSSNI3 ABSORBER BANDGAP AND THICKNESS FOR EFFICIENT LEAD-FREE PEROVSKITE SOLAR CELLS**
Mustapha AIT LAMINE Hamid EZ-ZAHRAOUY	*Mohammed V University in Rabat, Morocco*	**QUANTUM TELEPORTATION AND ENTANGLEMENT VIA QUANTUM CHANNELS IN BIMETALLIC FE2CU2 BASED ON SPIN-1/2 ISING-HEISENBERG CHAIN MODEL**
Khalil LOUKHSSAMI	*Morocco*	**ERGOTROPY AND QUANTUM CORRELATIONS IN A DRIVEN TWO-DOUBLE-QUANTUM-DOT QUANTUM BATTERY UNDER 1/F CHARGE NOISE**
Farouq Abba WABI Aliyu Muhammad ZABI	*Federal University of Health Sciences Azare, Nigeria* *Federal Polytechnic Kaltungo, Nigeria*	**GUARANTEED PURSUIT TIME IN A DIFFERENTIAL GAME WITH COORDINATE-WISE GEOMETRIC CONSTRAINTS**
Sama'ila YAKUBU Prof. Mohammed SALEH	*Bayero University Kano, Nigeria*	**A QUANTITATIVE REVIEW ON THE PHYSICAL, PHYSIOLOGICAL, AND STATISTICAL PRINCIPLES BEHIND DOWSING IN GROUNDWATER EXPLORATION**
Vadim K. GONCHAROV Polina D. KARPUK	*Saint-Petersburg State Marine Technical University, Russia*	**INVESTIGATION OF DYNAMIC EFFECTS OF WIND DRIFT OF ICE FIELDS**
Amina LACHGUER Prof. Dr. Abdenbi ELYAMANI Prof. Dr. Abdelkarim ZATNI Fatima BOUMRIT Kenza AIT ALI OUADDI	*Ibn Zohr University, Morocco*	**SEMICONDUCTOR OPTICAL AMPLIFIERS AS KEY ENABLERS FOR ADVANCED OPTICAL SIGNAL PROCESSING AND NETWORKING**

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Session-1

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HEAD OF SESSION: Asst. Prof. Dr. Raf Raf Shakil ANSARI

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Asst. Prof. Dr. K. R. PADMA K. R. DON	*Sri Padmavati Mahila Visvavidyalayam, India* *Bharath Institute of Higher Education & Research (BIHER), India*	**PLANT-DERIVED CHOLINESTERASE INHIBITORS: A STUDY OF PLECTRANTHUS AMBOINICUS AND ARAUCARIA COLUMNARIS**
Dr. Chokri BAYOUDH Yassmine GHRAIRI Afifa MAJDOUB Prof. Dr. Taoufik BETTAIEB	*Regional Research Centre on Horticulture and Organic Agriculture (CRRHAB), Tunisia*	**EFFICACY OF ROSEMARY AND THYME ESSENTIAL OILS ON PEAR (PYRUS COMMUNIS L.) EXPLANT EVOLUTION ON IN VITRO ESTABLISHMENT PHASE**
Ahmad RAZA Muhammad Tajammal HUSSAIN	*Government College University Faisalabad, Pakistan* *University of Agriculture Faisalabad, Pakistan*	**CLIMATE CHANGE, FOOD SECURITY, AND SUSTAINABLE FOOD PRODUCTION: CHALLENGES AND OPPORTUNITIES FOR RESILIENT FOOD SYSTEMS**
Asst. Prof. Dr. Raf Raf Shakil ANSARI	*Sharda University, India*	**WHO IS THE MONSTER? POSTHUMAN OTHERNESS AND THE CRISIS OF HUMAN EXCEPTIONALISM IN I AM LEGEND**
Alou YACOUBOU	*Université André Salifou, Niger Republic*	**TRAUMA IN POST-INDEPENDENT AFRICAN FICTION: A PSYCHOANALYTIC READING OF ISHMAEL BEAH'S LITTLE FAMILY**
Amadou SALAMI Kpèassi Kafoui Michée SAGBOHAN David Antoine SAGNO	*University of Kindia, Republic of Guinea* *University of Abomey-Calavi, Republic of Benin*	**METADISCOURSE STRATEGIES IN JOE BIDEN'S MARCH 1, 2022 SPEECH: A LINGUISTIC ANALYSIS**
C. Ashmitha CHELLAM Assoc. Prof. Dr. C. VAIRAVAN	*Academy of Maritime Education and Training Deemed to be University, India*	**DERANGEMENT OF SCALE: PLANETARY ECOCRITICISM AND ANTHROPOCENE FORM IN RICHARD POWERS'S PLAYGROUND**
Lect. Mariia KULESHIR	*Kyiv National Linguistic University, Ukraine*	**THE LANGUAGE OF SCHOOL PANDEMONIUM: CREATING HUMOR AND CHARACTER IN JEREMY STRONG'S 'PANDEMONIUM AT SCHOOL'**
Prof. Dr. Fatima Sadat YAHYAPOOR Sanaz HEMMATPOUR	*Urmia University, Iran*	**"SO IT GOES": A LACANIAN READING OF THE SLAUGHTERHOUSE-FIVE BY KURT VONNEGUT**
Fatima AITABELLA S. AGOUNAD Z. MOUTAKKI	*Abdelmalek Essaâdi University, Morocco*	**TOWARD ROBUST AND ADAPTIVE IMAGINED SPEECH RECOGNITION SYSTEMS FOR BRAIN-COMPUTER INTERFACES**

ONLINE
Session-1

SESSION · HALL
Session-1 · Hall-5

DATE
27 September 2026

TIME
10:00 – 12:00

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HEAD OF SESSION: Prof. Dr. Behzad BARADARAN

AUTHOR(S)	ORGANISATION	TOPIC TITLE
Prof. Alexander PLAKIDA Svetlana TRAPEZNIKOVA Victoria CHERNYAK Igor BURDIN	*Odesa National Medical University, Ukraine*	**EFFECTIVENESS OF INTERACTIVE SENSORY SYSTEM "BRIOLIGHT" IN COMPLEX REHABILITATION OF CHILDREN WITH PSYCHOMOTOR SPEECH DELAY**
Kosar TALEB Alireza AHAMDI Prof. Dr. Behzad BARADARAN Reza SAFARALIZADEH Mohammad KHALAJ-KONDORI	*University of Tabriz, Iran*	**PHOTODYNAMIC THERAPY WITH ZINC PHTHALOCYANINE RESULTS IN INCREASED LEVELS OF APOPTOSIS AND REDUCTION IN STEMNESS FEATURES OF MIA PACA-2 PANCREATIC CANCER CELL LINE**
Samuel Maida DOGO Prof. Katrina A. KORB Prof. Oluyomi O. AKINTUNDE	*University of Jos, Nigeria*	**EFFECTS OF COGNITIVE BEHAVIOURAL INTERVENTION ON ANXIETY AMONG SENIOR SECONDARY SCHOOL STUDENTS IN CHIKUN LOCAL GOVERNMENT AREA OF KADUNA STATE, NIGERIA**
Maedah Ayyed KHALAF Zahraa Fadhil ABBAS Firas ALALI Marwa JAWAD Vitalii MELNYCHUK Asaad Sh. M. ALHESNAWI	*University of Kerbala, Iraq*	**MOLECULAR, SEQUENCE AND PHYLOGENETIC ANALYSIS OF NEOSPOROSIS IN DOMESTIC PIGEONS IN KARBALA PROVINCE, IRAQ**
Chaima MOUFFOUK Soumia MOUFFOUK Hamada HABA Abdelbasset TAMERSIT Sara MOUFFOUK	*University of Batna 2 Mustapha Benboulaid; University of Batna 1, Algeria*	**IN VIVO, IN VITRO, AND IN SILICO PHARMACOLOGICAL EFFECTS OF THE MEDICINAL SPECIES LOMELOSIA STELLATA L.**
Saheed Ayodeji ADEKOLA Afeez Oladimeji BUHARI Abidemi Nurat AKINBAMI Frank Lale NWAFORBE	*University of Abuja, Nigeria*	**INTEGRATING CANCER SCREENING INTO FAMILY PLANNING: LESSONS FROM EARLY-ONSET BREAST AND GYNECOLOGIC CANCERS IN NIGERIA**
Lilian UKPKONG Saheed Ayodeji ADEKOLA Aisha OHEIKU Amos NWORIE	*University of Abuja, Nigeria*	**BREAST CANCER AND HARMFUL CHEMICAL & ENVIRONMENTAL EXPOSURES: THE ROLE OF CONSUMER PRODUCTS IN BREAST CANCER RISK**
Mohamed DABBABI Maroua TRIGUI Yosra MEJDOUB Salima BRADAI Fedi BEN DHAOU Mondher KASSIS	*CHU Habib Bourguiba, Tunisia*	**SMOKING CESSATION STRATEGIES IN CARDIOVASCULAR PREVENTION: A NARRATIVE REVIEW OF WORLD HEALTH ORGANIZATION GUIDELINES**
Muhammad Riaz Baig CHUGHTAI Prof. Dr. Satheesh Babu NATRANJAN Assoc. Prof. Dr. Mazhar ALI	*Lincoln University College, Malaysia*	**AEROBIC-BASED CARDIAC REHABILITATION IMPROVES FUNCTIONAL CAPACITY AFTER CORONARY ARTERY BYPASS GRAFTING: A FOCUSED COMPARISON WITH CONVENTIONAL CARE**
Lect. Ahmed Abdul Ghaffar GAWAS Asst. Prof. Emhemed Khalifa GERISH	*Faculty of Medical Sciences and Technologies, Libya*	**DIABETIC NEPHROPATHY AND ITS ASSOCIATED FACTORS AMONG HAEMODIALYSIS PATIENTS WITH DIABETES MELLITUS IN TRIPOLI, LIBYA: A HOSPITAL-BASED CROSS-SECTIONAL STUDY**

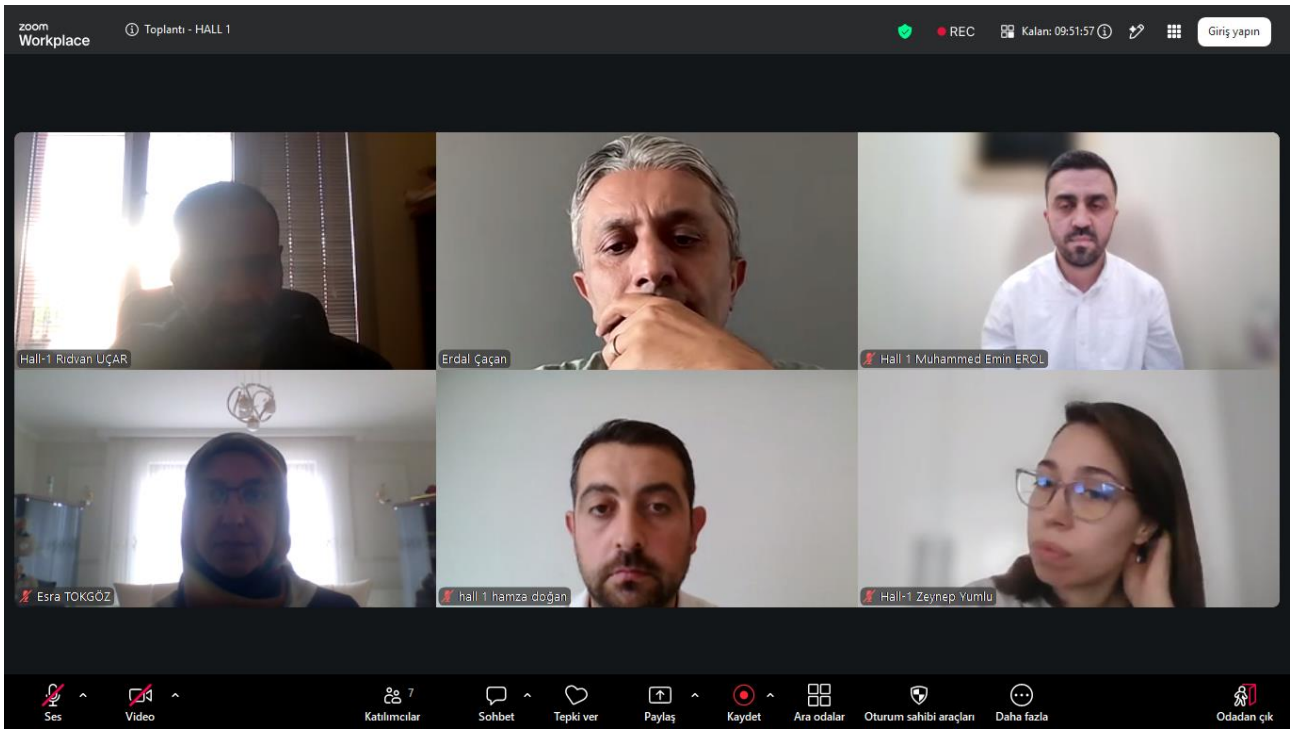
CONFERENCE GALLERY

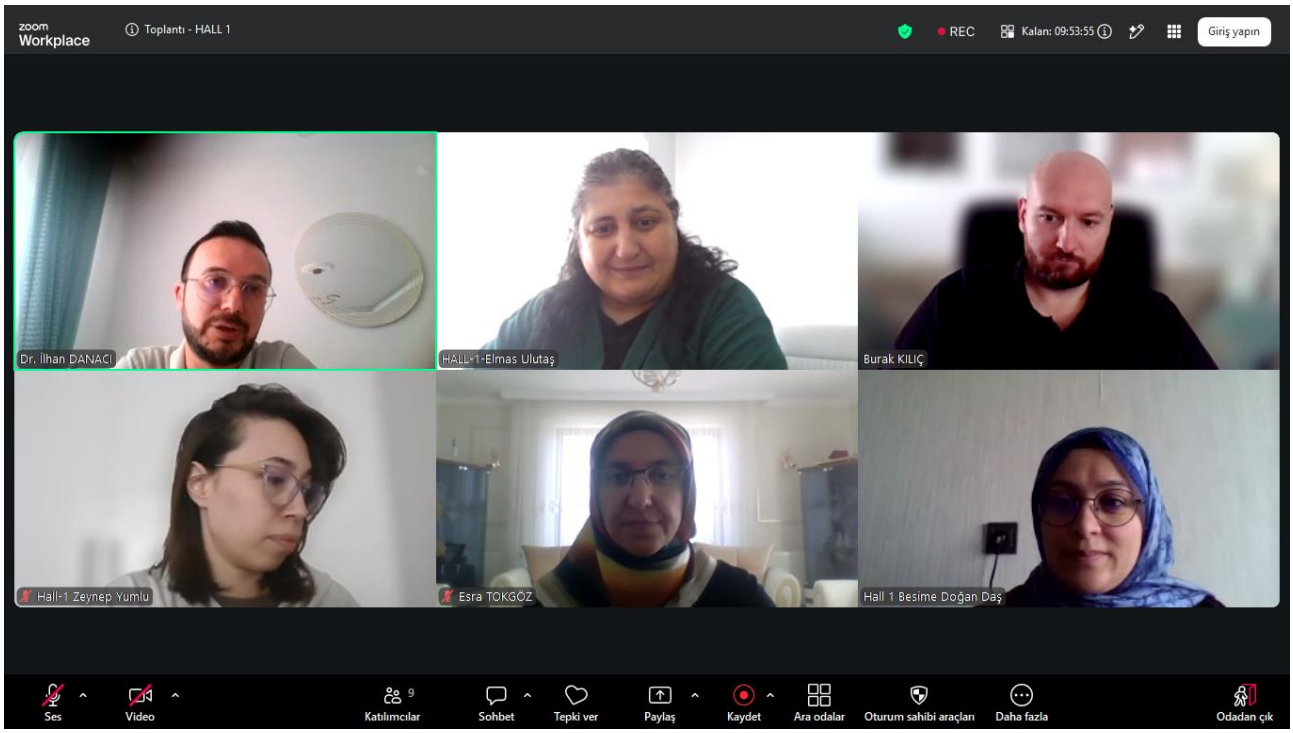


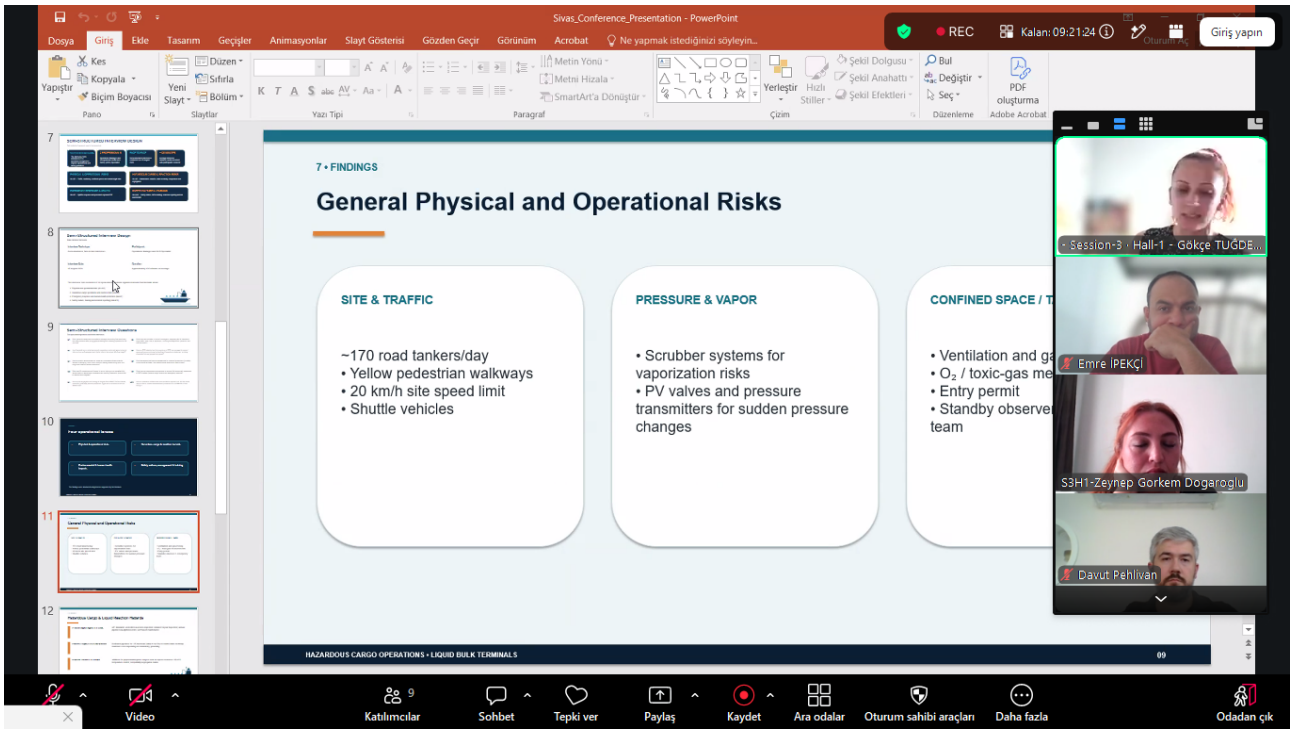


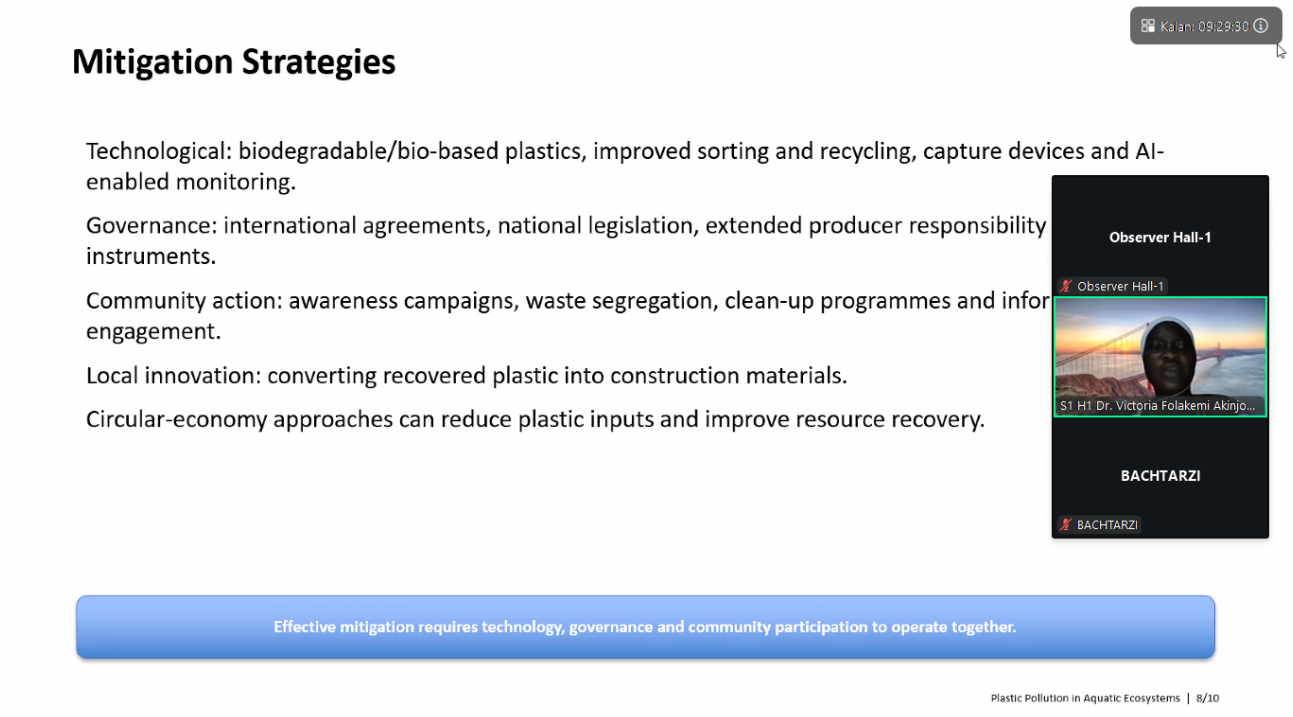

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5. ULUSLARARASI BİLİMSEL ARAŞTIRMALAR
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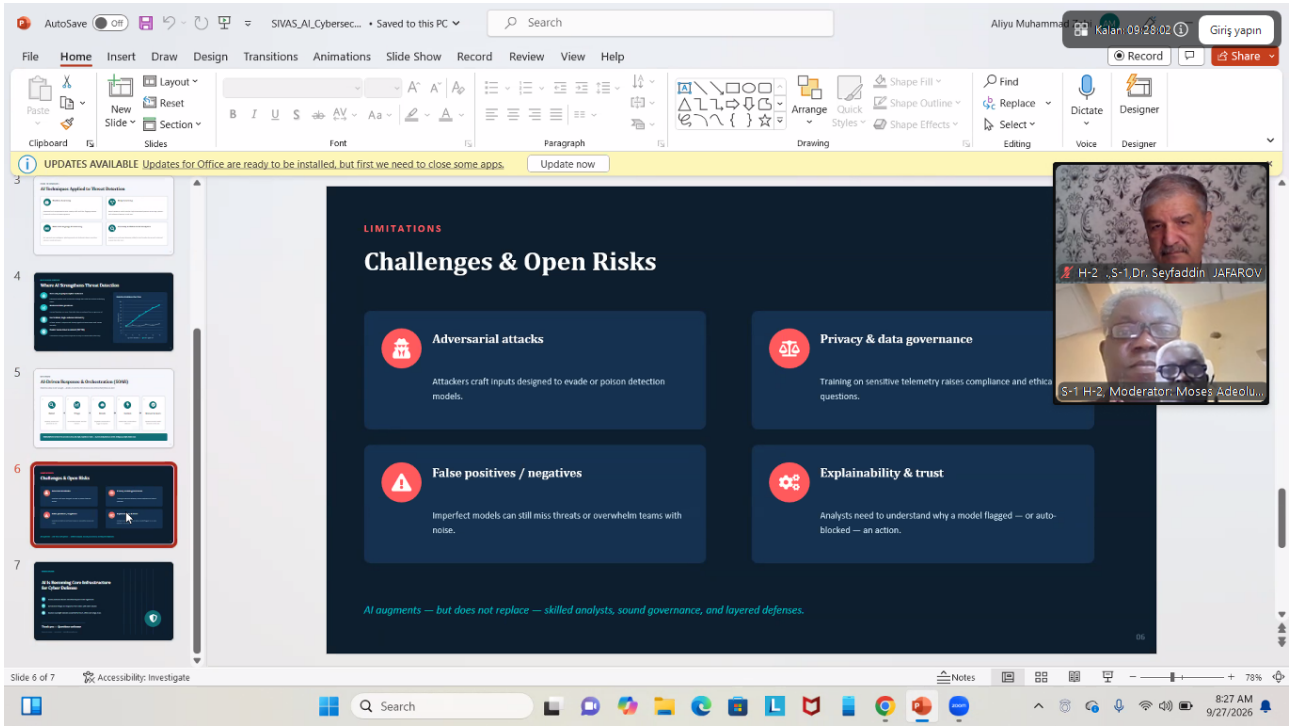

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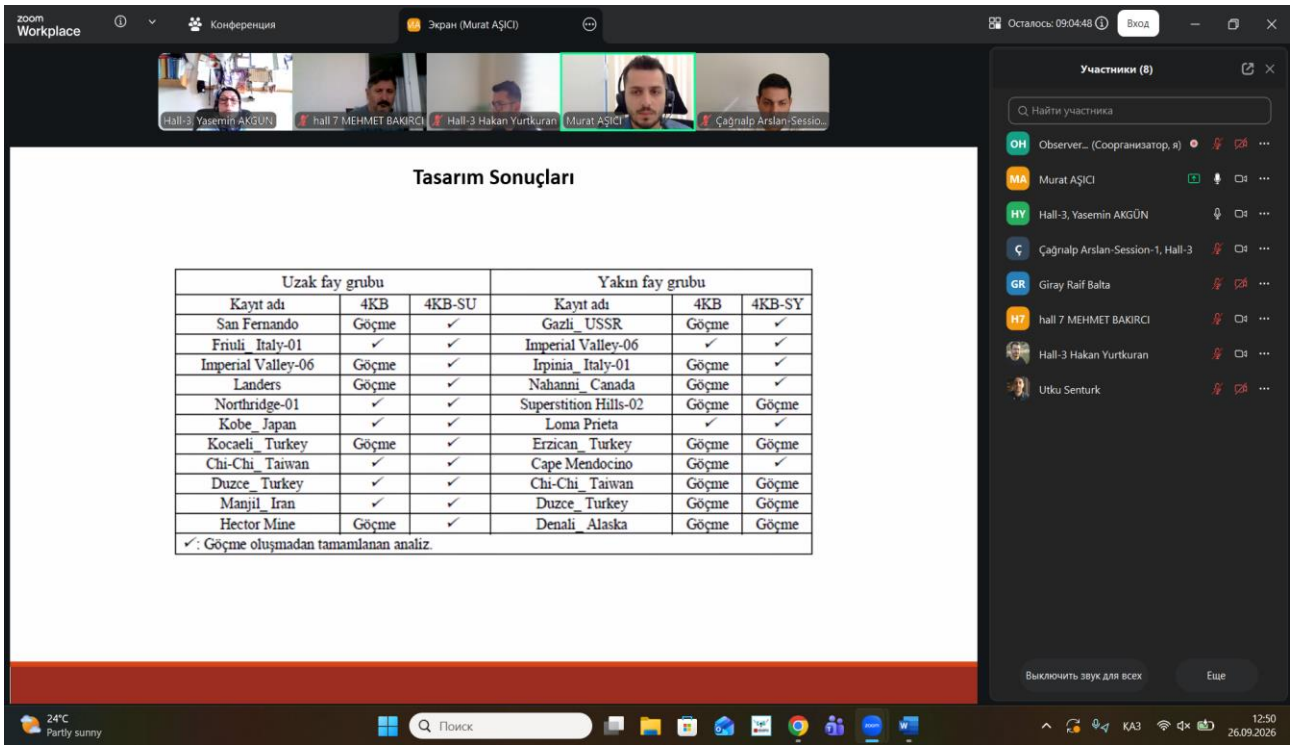

zoom Workplace
Toplantı - HALL 1
REC
Kalan: 09:51:57
Giriş yapın
Hall-1 Rıdvan UÇAR
Erdal Çaçan
Hall 1 Muhammed Emin EROL
Esra TOKGÖZ
hall 1 hamza doğan
Hall-1 Zeynep Yumlu
Ses
Video
Katılımcılar
7
Sohbet
Tepki ver
Paylaş
Kaydet
Ara odalar
Oturum sahibi araçları
Daha fazla
Odadan çık


zoom Workplace
Toplantı - HALL 1
REC
Kalan: 09:53:55
Giriş yapın
Dr. İlhan DANACI
HALL-1-Elmas Ulutaş
Burak KILIÇ
Hall-1 Zeynep Yumlu
Esra TOKGÖZ
Hall 1 Besime Doğan Daş
Ses
Video
Katılımcılar
9
Sohbet
Tepki ver
Paylaş
Kaydet
Ara odalar
Oturum sahibi araçları
Daha fazla
Odadan çık


Sivas_Conference_Presentation - PowerPoint
REC
Kalan: 09:21:24
Giriş yapın
7 • FINDINGS
General Physical and Operational Risks
SITE & TRAFFIC
~170 road tankers/day
• Yellow pedestrian walkways
• 20 km/h site speed limit
• Shuttle vehicles
PRESSURE & VAPOR
• Scrubber systems for vaporization risks
• PV valves and pressure transmitters for sudden pressure changes
CONFINED SPACE / T
• Ventilation and ga
• O2 / toxic-gas me
• Entry permit
• Standby observer team
HAZARDOUS CARGO OPERATIONS - LIQUID BULK TERMINALS
09
Session-3 : Hall-1 - Gökçe TUĞDE...
Emre İPEKÇİ
S3H1-Zeynep Görkem Doğaroğlu
Davut Pehlivan
Video
Katılımcılar
Sohbet
Tepki ver
Paylaş
Kaydet
Ara odalar
Oturum sahibi araçları
Daha fazla
Odadan çık


Kalan: 09:29:30
Mitigation Strategies
Technological: biodegradable/bio-based plastics, improved sorting and recycling, capture devices and AI-enabled monitoring.
Governance: international agreements, national legislation, extended producer responsibility instruments.
Community action: awareness campaigns, waste segregation, clean-up programmes and infor engagement.
Local innovation: converting recovered plastic into construction materials.
Circular-economy approaches can reduce plastic inputs and improve resource recovery.
Observer Hall-1
Observer Hall-1
S1 H1 Dr. Victoria Folakemi Akinjo...
BACHTARZI
BACHTARZI
Effective mitigation requires technology, governance and community participation to operate together.
Plastic Pollution in Aquatic Ecosystems | 8/10



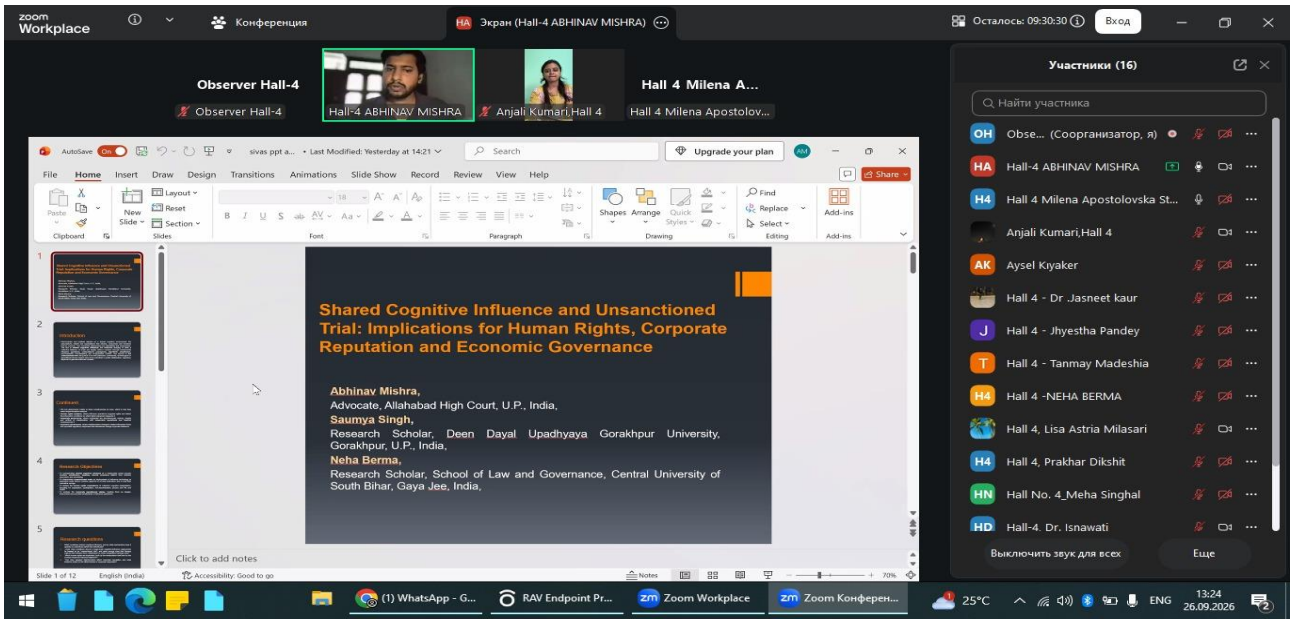


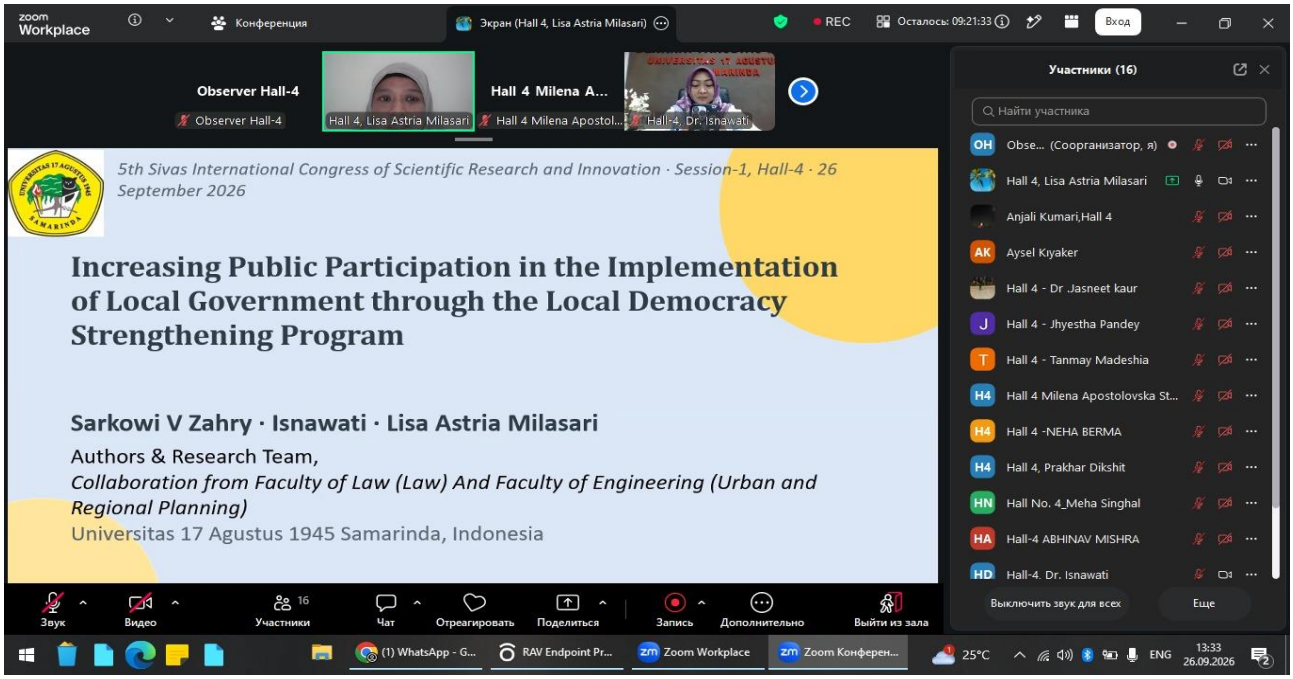
Uzak fay grubu			Yakın fay grubu		
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San Fernando	Göçme	✓	Gazli_ USSR	Göçme	✓
Friuli_ Italy-01	✓	✓	Imperial Valley-06	✓	✓
Imperial Valley-06	Göçme	✓	Irpinia_ Italy-01	Göçme	✓
Landers	Göçme	✓	Nahanni_ Canada	Göçme	✓
Northridge-01	✓	✓	Superstition Hills-02	Göçme	Göçme
Kobe_ Japan	✓	✓	Loma Prieta	✓	✓
Kocaeli_ Turkey	Göçme	✓	Erzican_ Turkey	Göçme	Göçme
Chi-Chi_ Taiwan	✓	✓	Cape Mendocino	Göçme	✓
Duzce_ Turkey	✓	✓	Chi-Chi_ Taiwan	Göçme	Göçme
Manjil_ Iran	✓	✓	Duzce_ Turkey	Göçme	Göçme
Hector Mine	Göçme	✓	Denali_ Alaska	Göçme	Göçme

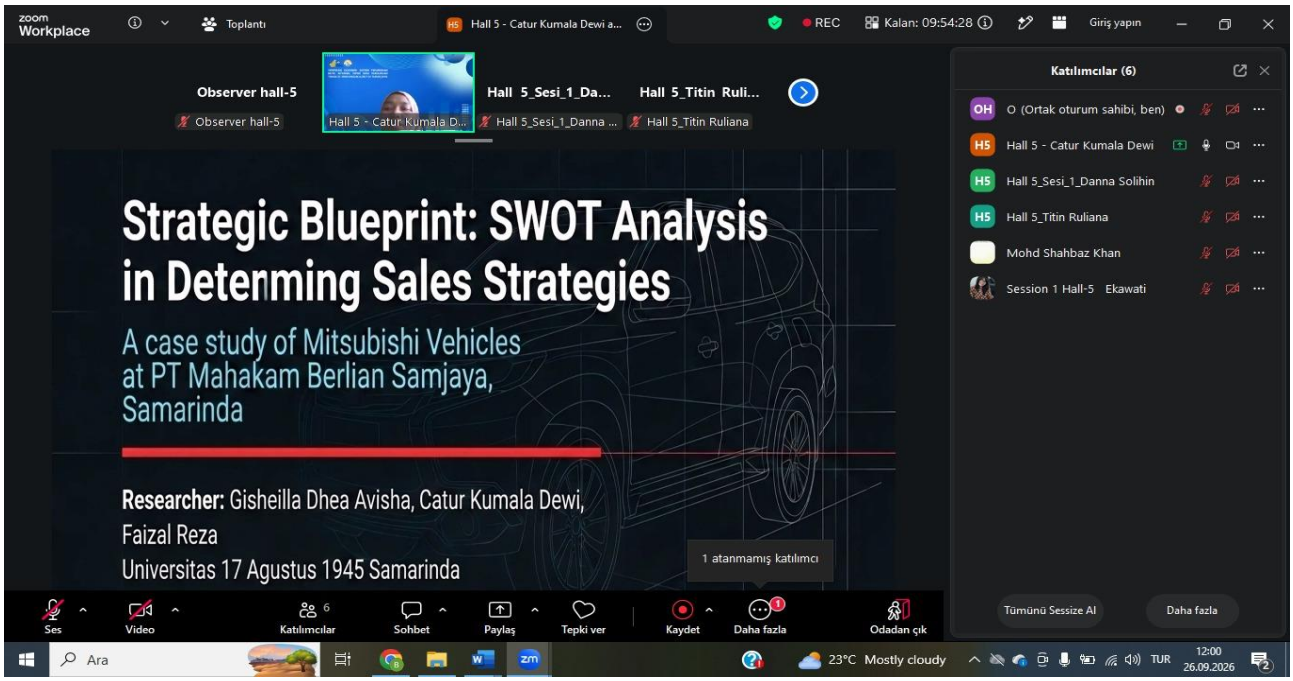
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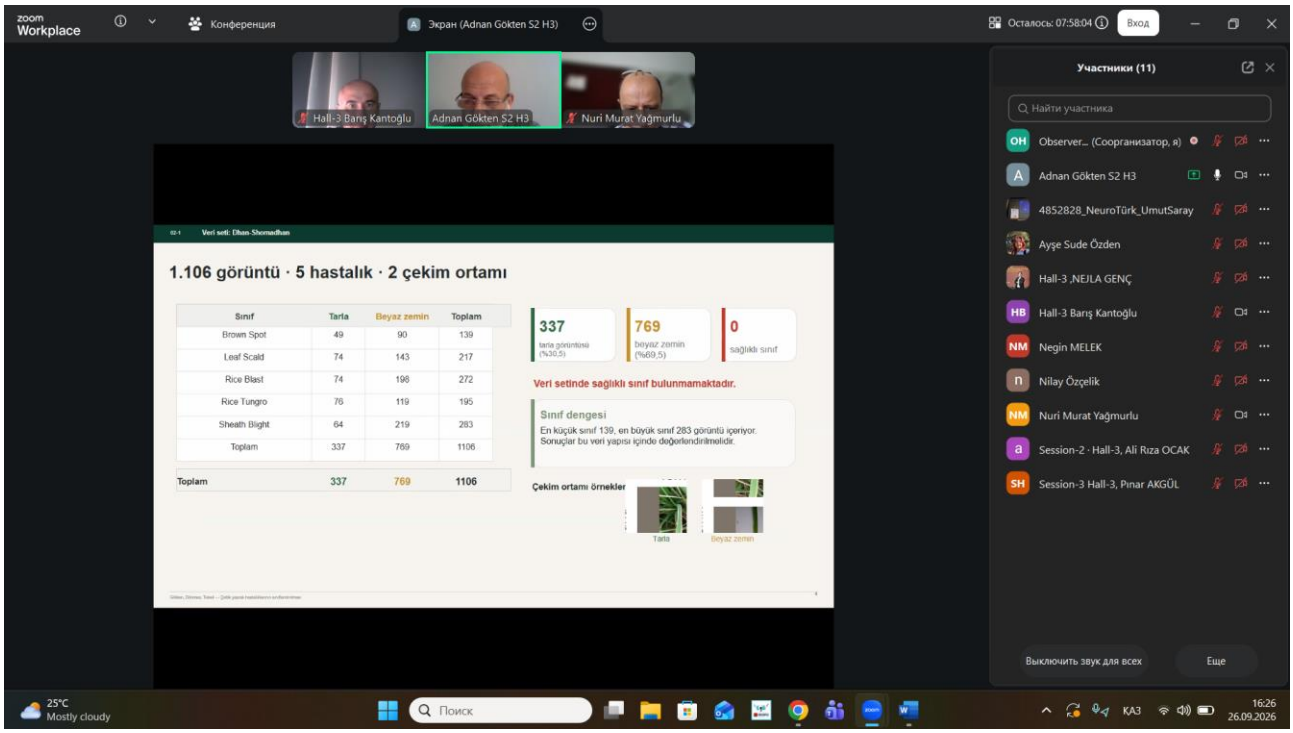

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Sayısal Analizi:
Doğrulama ve İnceleme
Участники (8)
Observer... (Соорганизатор, я)
Giray Raif Balta
Hall-3, Yasemin AKGÜN
Çağrıalp Arslan-Session-1, Hall-3
hall 7 MEHMET BAKIRCI
Hall-3 Hakan Yurtkuran
Murat AŞICI
Utku Senturk

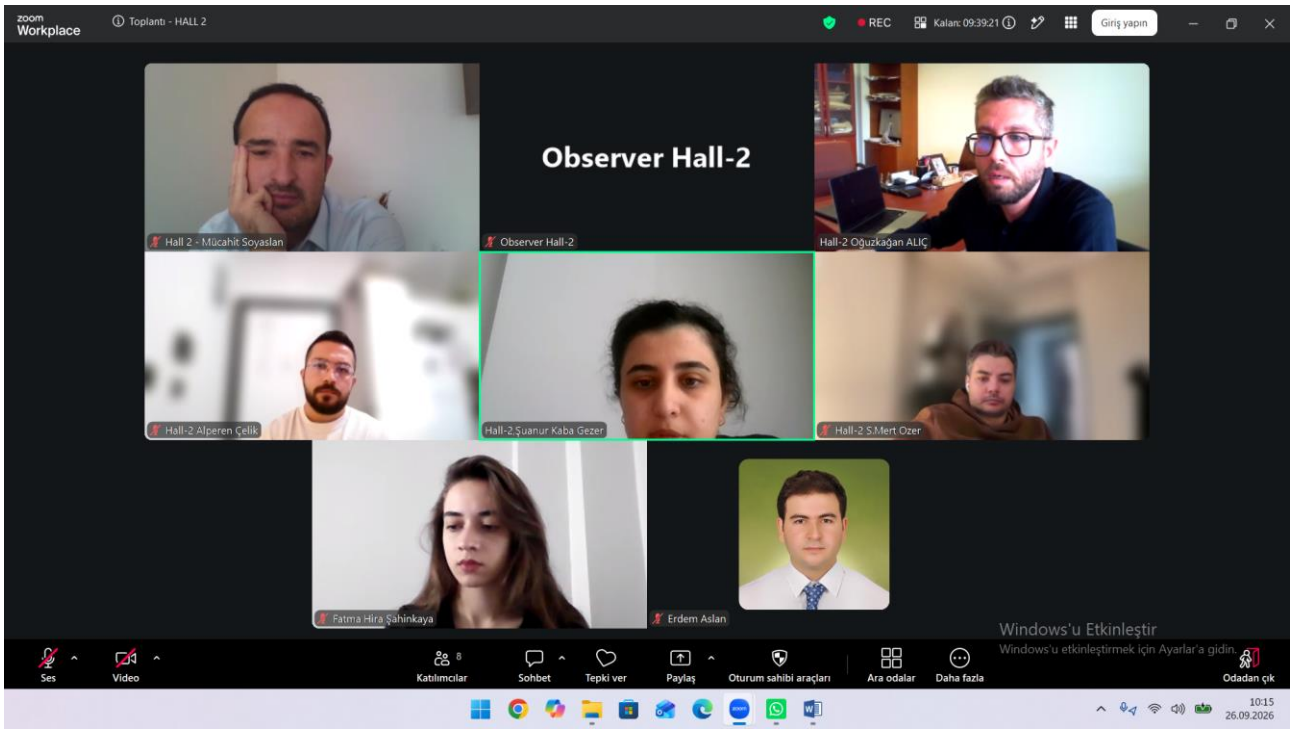

Paradigm Transformation of Indonesian
Higher Education Quality Assurance
Legal Gap Analysis of Permendiktisaintek No. 39/2025
Transition and Quality Implementation Strategies
Ekawati, Isnawati, Sarikun
Universitas 17 Agustus 1945 Samarinda
International Congress on
Scientific Researches
September 25-27, 2026
Sivas University, Türkiye
Участники (17)
Hall-4, Sintya Irawati
Hall 4 Milena Apostolovska St...
Anjali Kumari,Hall 4
Aysel Kıyaker
Dr. Poonam Kumari (Hall-4)
Hall 4 - Dr Jasneet kaur
Hall 4 - Jhyestha Pandey
Hall 4 - Tanmay Madeshia
Hall 4 -NEHA BERMA
Hall 4, Lisa Astria Milasari
Hall 4, Prakhar Dikshit
Hall No. 4 Meha Singhal

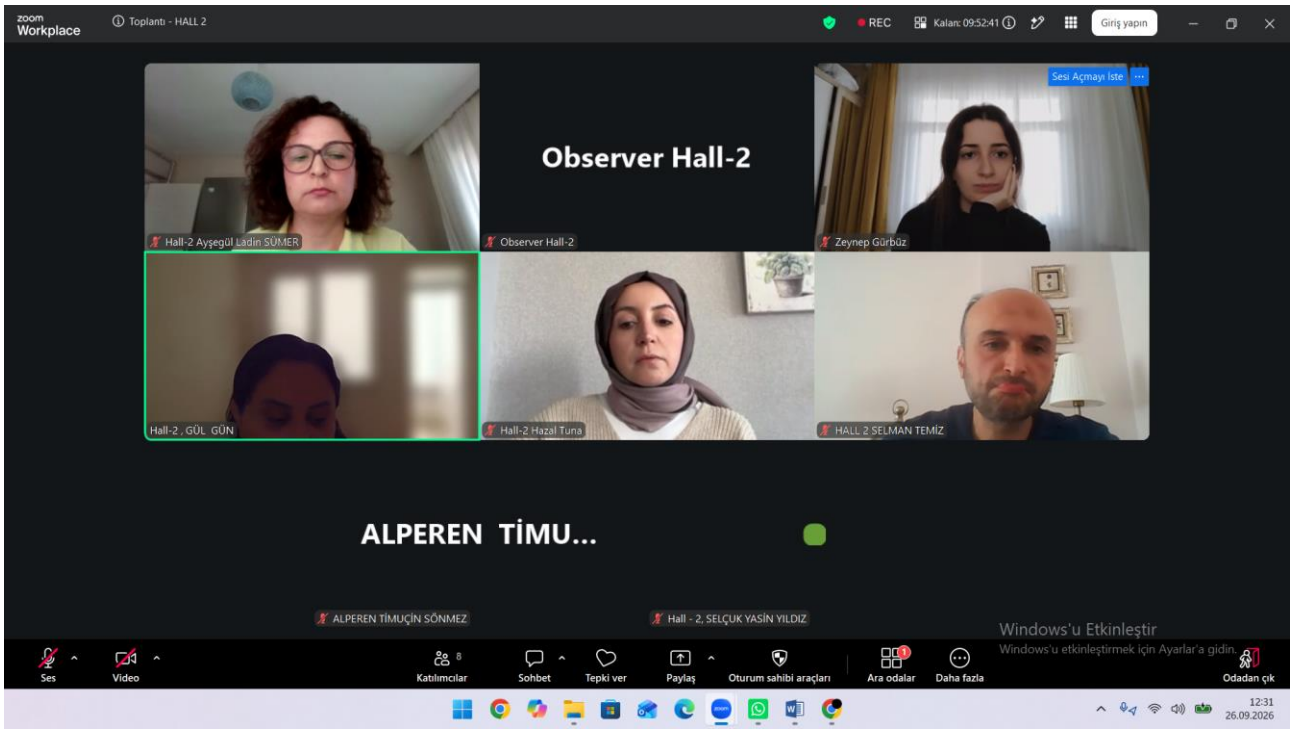

Observer Hall-4
Hall-4 ABHINAV MISHRA
Anjali Kumari,Hall 4
Hall 4 Milena A...
Hall 4 Milena Apostolov...
Shared Cognitive Influence and Unsanctioned Trial: Implications for Human Rights, Corporate Reputation and Economic Governance
Abhinav Mishra,
Advocate, Allahabad High Court, U.P., India,
Saumya Singh,
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Участники (16)


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Hall 4 Milena A...
Hall-4. Dr. Isnawati
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Increasing Public Participation in the Implementation of Local Government through the Local Democracy Strengthening Program
Sarkowi V Zahry · Isnawati · Lisa Astria Milasari
Authors & Research Team,
Collaboration from Faculty of Law (Law) And Faculty of Engineering (Urban and Regional Planning)
Universitas 17 Agustus 1945 Samarinda, Indonesia
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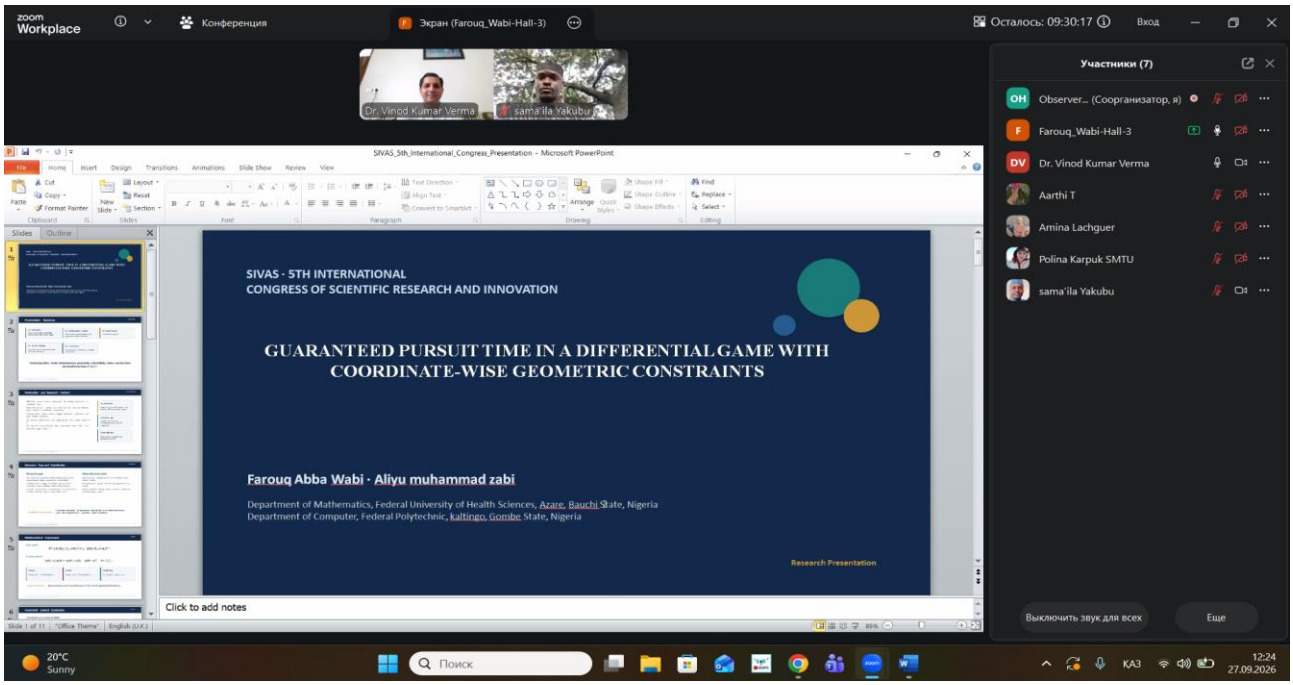

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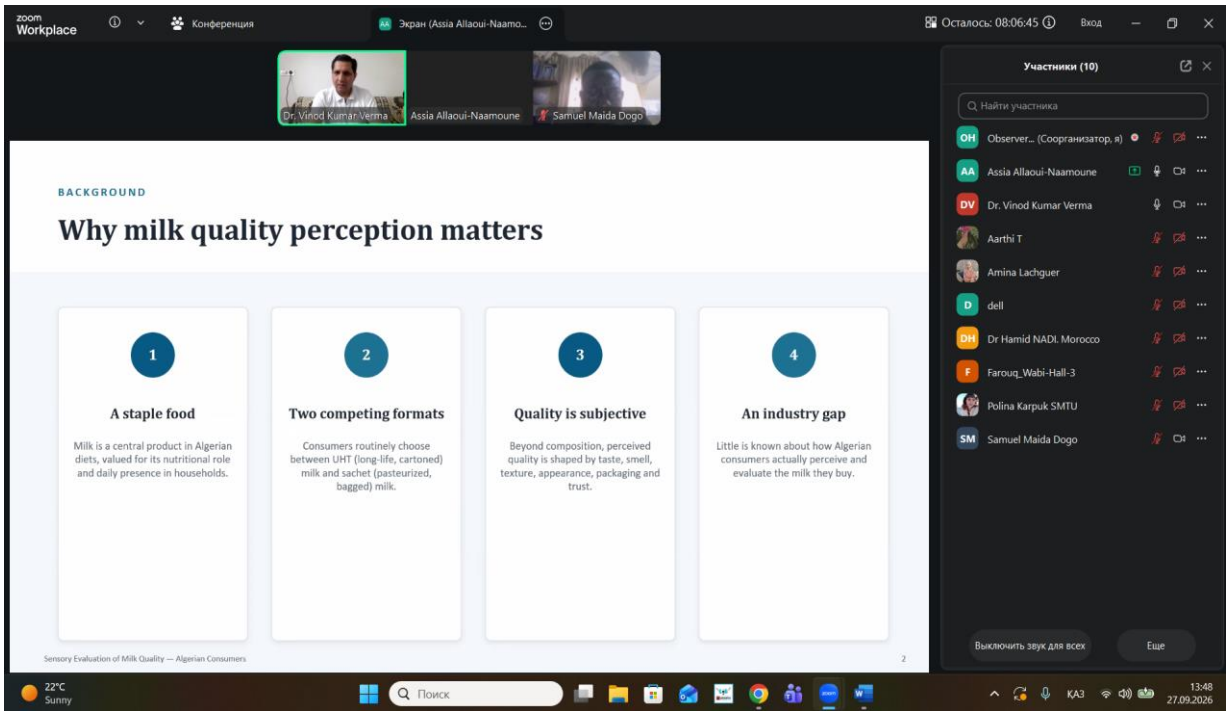

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Department of Mathematics, Federal University of Health Sciences, Azare, Bauchi State, Nigeria
Department of Computer, Federal Polytechnic, Kaltingo, Gombe State, Nigeria
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Dr. Vinod Kumar Verma
Assia Allaoui-Naamoune
Samuel Maida Dogo
BACKGROUND
Why milk quality perception matters
1
A staple food
Milk is a central product in Algerian diets, valued for its nutritional role and daily presence in households.
2
Two competing formats
Consumers routinely choose between UHT (long-life, cartoned) milk and sachet (pasteurized, bagged) milk.
3
Quality is subjective
Beyond composition, perceived quality is shaped by taste, smell, texture, appearance, packaging and trust.
4
An industry gap
Little is known about how Algerian consumers actually perceive and evaluate the milk they buy.
Sensory Evaluation of Milk Quality — Algerian Consumers
Участники (10)

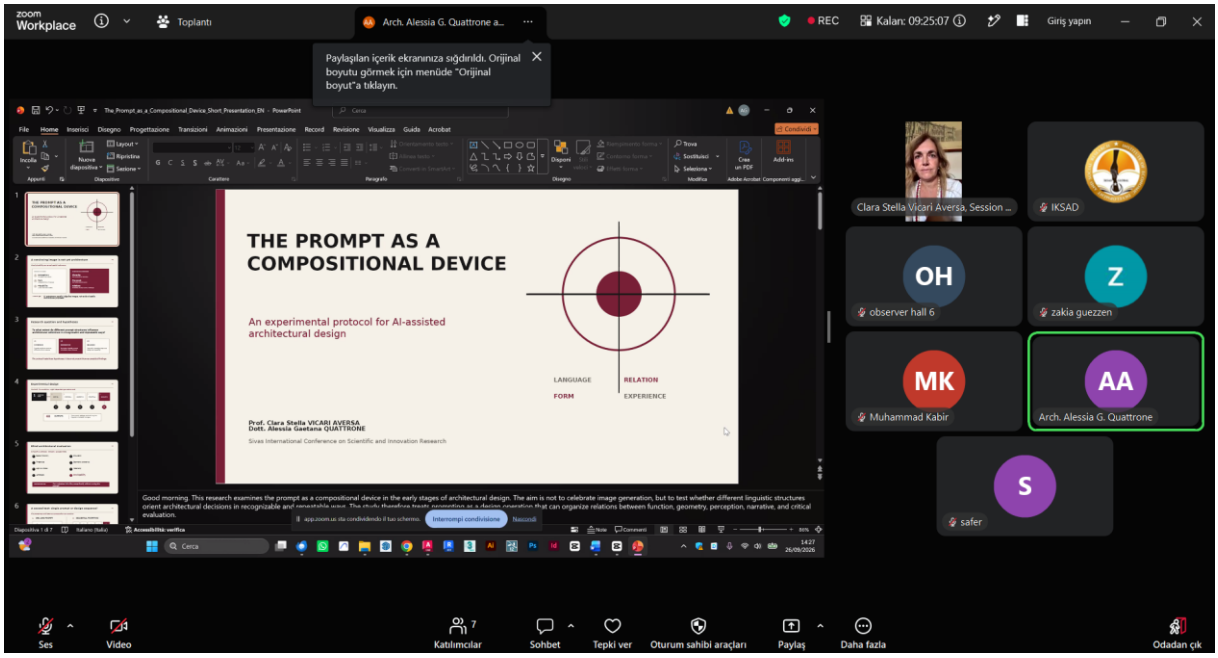

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An experimental protocol for AI-assisted architectural design
Prof. Clara Stella VICARI AVERSA
Dott. Alessia Gaetana QUATTRONE
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FORM
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Muhammad Kabir
Arch. Alessia G. Quattrone
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ESTIMATION OF BODY MASS INDEX FROM 12-LEAD ECG SIGNALS USING MINIROCKET FEATURES AND BAGGED ENSEMBLE NEURAL NETWORKS

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ABSTRACT
Accurate estimation of body mass index (BMI) categories from routinely acquired physiological signals may provide a practical alternative when direct anthropometric measurements are unavailable or difficult to obtain. However, inferring BMI from electrocardiogram (ECG) recordings is challenging because the relationship between body composition and cardiac electrical activity is indirect and affected by substantial inter-individual variability, cardiac conditions, and signal noise. In this study, we propose an efficient ensemble machine learning framework for three-class BMI classification into Underweight, Normal, and Overweight/Obese categories using 6,586 12-lead ECG recordings from the PTB-XL dataset. The ECG signals were sampled at 100 Hz, bandpass-filtered between 0.5 and 40 Hz, and independently normalized across channels. Two complementary time-series feature-extraction methods were employed to transform the multivariate ECG signals into a high-dimensional feature representation capable of capturing discriminative temporal and morphological patterns: MiniRocket, using 10,000 convolutional kernels, and QUANT, a minimalist interval-based transform that computes quantile features over dyadic intervals of the signal. To reduce redundancy and computational complexity, the combined feature set was standardized and projected onto 300 principal components using Principal Component Analysis (PCA), after which demographic information, including age and sex, was incorporated. The resulting feature representation was classified using a nine-model bagged Multi-Layer Perceptron (MLP) ensemble comprising three complementary hidden-layer configurations and three independent random initializations per configuration. Model performance was assessed using stratified five-fold cross-validation. The proposed ensemble achieved fold-level accuracies ranging from 62.79% to 65.17%, with a mean accuracy of 63.83% ± 0.77% and a mean balanced accuracy of 45.84% ± 0.93%. The lower balanced accuracy reflects the substantial class imbalance, with Underweight cases accounting for only 4.2% of the cohort. For the clinically more prevalent Normal and Overweight/Obese categories, the model achieved an isolated classification accuracy of 66.44%. Overall, the findings indicate that ECG-derived temporal morphology, particularly when combined with demographic information, contains measurable information related to BMI category and can support non-invasive opportunistic biometric estimation, while also demonstrating the need for improved strategies for minority-class prediction.
Keywords: Body Mass Index, MiniRocket, QUANT, Bagged Ensemble MLP, Biometric Estimation.

ÖZET
Rutin olarak elde edilen fizyolojik sinyallerden vücut kitle indeksi (VKİ) kategorilerinin doğru şekilde tahmin edilmesi, doğrudan antropometrik ölçümlerin bulunmadığı veya elde edilmesinin zor olduğu durumlarda pratik bir alternatif sunabilir. Ancak vücut bileşimi ile kardiyak elektriksel aktivite arasındaki ilişkinin dolaylı olması, bireyler arası yüksek varyasyondan, kardiyak durumlardan ve sinyal gürültüsünden etkilenmesi nedeniyle elektrokardiyogram (EKG) kayıtlarından VKİ tahmini yapmak oldukça güçtür. Bu çalışmada, PTB-XL veri setinden alınan 6.586 adet 12 derivasyonlu EKG kaydı kullanılarak VKİ'nin Zayıf, Normal ve Fazla Kilolu/Obez şeklinde üç sınıfta sınıflandırıldığı verimli bir topluluk (ensemble) makine öğrenmesi mimarisi önerilmektedir. EKG sinyalleri 100 Hz frekansta

örneklenmiş, 0,5-40 Hz arasında bant geçiren filtreden geçirilmiş ve kanallar arasında bağımsız olarak normalize edilmiştir. Ayrıştırıcı zamansal ve morfolojik örüntüleri yakalayabilen yüksek boyutlu bir öznitelik temsiline çok değişkenli EKG sinyallerini dönüştürmek amacıyla, biri 10.000 konvolüsyon çekirdeği kullanan MiniRocket, diğeri sinyalin diyadik aralıklarından kantil öznitelikleri hesaplayan minimalist bir aralık tabanlı yöntem olan QUANT olmak üzere iki tamamlayıcı zaman serisi öznitelik çıkarım yöntemi uygulanmıştır. Gereksiz verileri ve hesaplama karmaşıklığını azaltmak için çıkarılan öznitelikler standartlaştırılmış ve Temel Bileşen Analizi (PCA) kullanılarak 300 temel bileşene indirgenmiş, ardından yaş ve cinsiyet gibi demografik bilgiler sürece dahil edilmiştir. Elde edilen öznitelik temsili; üç tamamlayıcı gizli katman konfigürasyonu ve konfigürasyon başına üç bağımsız rastgele başlatma içeren, dokuz modelli bir torbalanmış (bagged) Çok Katmanlı Algılayıcı (MLP) topluluğu ile sınıflandırılmıştır. Model performansı, katmanlı 5 katlı çapraz doğrulama (stratified 5-fold cross-validation) ile değerlendirilmiştir. Önerilen topluluk modeli %62,79 ile %65,17 arasında değişen katman düzeyinde doğruluk değerleri elde etmiş; ortalama doğruluk %63,83 ± %0,77 ve ortalama dengeli doğruluk ise %45,84 ± %0,93 olarak gerçekleşmiştir. Düşük dengeli doğruluk oranı, Zayıf vakaların kohortun yalnızca %4,2'sini oluşturduğu belirgin sınıf dengesizliğini yansıtmaktadır. Klinik açıdan daha yaygın olan Normal ve Fazla Kilolu/Obez kategorileri için model, %66,44'lük izole bir sınıflandırma doğruluğuna ulaşmıştır. Genel olarak bulgular, EKG kaynaklı zamansal morfolojinin - özellikle demografik bilgilerle birleştirildiğinde- VKİ kategorisiyle ilişkili ölçülebilir bilgiler içerdiğini ve invaziv olmayan fırsatçı biyometrik tahmini destekleyebileceğini gösterirken, aynı zamanda azınlık sınıfı (minority-class) tahmini için geliştirilmiş stratejilere ihtiyaç duyulduğunu ortaya koymaktadır.
Anahtar kelimeler: Vücut Kitle İndeksi, MiniRocket, QUANT, Torbalanmış Topluluk MLP, Biyometrik Tahmin.

Introduction

Accurate estimation of body mass index (BMI) and body weight is a fundamental prerequisite in clinical medicine, playing a pivotal role in optimizing pharmacokinetics and pharmacodynamics for weight-based medication dosing (Pai, 2012). In drugs with a narrow therapeutic window, such as vancomycin, under-dosing leads to treatment failure, whereas over-dosing can precipitate severe toxicity and adverse drug events (Rybak et al., 2020). Obtaining an accurate, physical scale weight, however, is frequently impossible in emergency and acute-care settings: patients presenting with trauma, altered mental status, cardiac arrest, or severe sedation, as well as comatose or bedridden individuals, cannot be placed on standard weighing scales (Maskin et al., 2010; Bloomfield, Steel, MacLennan, & Noble, 2006; Hall et al., 2013). In such urgent scenarios, clinicians often rely on visual estimation or surrogate reports from relatives, both of which are notoriously inaccurate and prone to significant error. Maskin et al. (2010) found that ICU staff's visual weight estimates had mean errors exceeding 11%, with 15–24% of cases exceeding a 20% error margin, and comparable inaccuracies have been reported for weight estimation in the emergency department (Hall et al., 2013). Such estimation errors can directly compromise weight-based dosing and patient safety, motivating the search for passive, point-of-care methods capable of inferring body mass category from routinely collected bio-signals.

Standard 12-lead electrocardiography (ECG) is universally acquired upon emergency department admission and during intensive care monitoring, making it an attractive candidate signal for such opportunistic estimation (Fraley, Birchem, Senkottaiyan, & Alpert, 2005). From a biophysical standpoint, variations in body mass alter the spatial propagation of electrical current from the myocardium to the chest wall surface (Sivasankaran et al., 2008). Increased subcutaneous adipose tissue, chest wall thickness, and epicardial fat accumulation are known to cause amplitude dampening, axis shifts, and subtle morphological alterations in ECG wave components (Sivasankaran et al., 2008; Li, Patel, Sun, Peters, & Ng, 2021). Building on this biophysical link, deep learning models—particularly convolutional neural networks (CNNs)—have been explored for biometric and anthropometric estimation from ECG waveforms, including age and sex prediction trained on nearly 500,000 patients (Attia et al., 2019) and direct BMI estimation on the UK Biobank cohort (Li et al., 2021). In a related but non-ECG line of work, Jeon, Lee, and Oh (2023) applied machine learning to demographic and lifestyle features to identify age-specific obesity risk factors, reflecting a broader interest in data-driven, non-invasive obesity screening. Such end-to-end deep architectures, however, are computationally expensive to train, prone to overfitting on the comparatively modest sample sizes available in most single-center ECG datasets, and offer limited interpretability of their intermediate representations.

While predicting exact continuous body weight from an indirect electrophysiological trace remains an exceptionally challenging and unsolved problem—owing to high inter-individual variability and confounding cardiac pathologies—developing reliable machine learning classifiers for BMI categories offers a more tractable and clinically useful stepping stone (Li et al., 2021; Wagner et al., 2020). Rather than adopting heavily parameterized deep learning architectures such as 1D-CNNs or ResNet variants, which are computationally prohibitive and prone to overfitting on bio-signal datasets, we propose a lightweight and efficient hybrid framework. Specifically, we combine two complementary, non-learned time-series transforms: the MiniRocket algorithm (Dempster, Schmidt, & Webb, 2021), which applies random convolutional kernels to rapidly capture high-dimensional temporal and morphological patterns, and QUANT (Dempster, Schmidt, & Webb, 2024), a minimalist interval-based transform that computes quantile features from dyadic intervals of the signal and its first- and second-order differences, capturing complementary distributional and shape information at a fraction of the computational cost of conventional CNNs. Following PCA-based dimensionality reduction of the fused MiniRocket+QUANT feature space, the resulting representation is combined with demographic covariates and classified using a 9-model Bagged Ensemble Multi-Layer Perceptron (MLP), a strategy designed to suppress model variance and mitigate overfitting without the training overhead of deep residual networks. Tested on 6,586 12-lead ECG records from the open-access PTB-XL dataset (Wagner et al., 2020), this work investigates the feasibility of 3-class BMI prediction (Underweight, Normal, Overweight/Obese) as a practical proof-of-concept for opportunistic biometric screening in acute clinical workflows.

The main contributions of this study are summarized as follows:

- **Ensemble Architecture for ECG Biometrics:** A novel, end-to-end framework combining 10,000 MiniRocket convolutional kernels, QUANT interval-quantile features, PCA dimensionality reduction, and a 9-model Bagged Ensemble MLP architecture is designed to effectively stabilize model variance across cross-validation folds.
- **Benchmark Superiority on the 3-Class BMI Task:** An overall 3-class accuracy of 63.83% and an isolated Normal/Overweight-Obese accuracy of 66.44% are achieved on the PTB-XL dataset (Wagner et al., 2020), outperforming the 51–56% 3-class accuracy ceiling reported for deep learning architectures on the UK Biobank dataset (Li et al., 2021).
- **Clinical Feasibility Evaluation:** A biophysical baseline is established, demonstrating that passive biometric classification from indirect ECG signals can approach performance levels reported for direct obesity-related cardiac screening measures (Fraley et al., 2005; Sivasankaran et al., 2008), thereby offering a viable, low-cost complement to physical anthropometry in settings where direct measurement is impractical.

Materials and Methods

The proposed framework integrates ECG-derived features with demographic information to classify patients into three BMI categories: Underweight, Normal, and Overweight/Obese. As illustrated in Figure 1, the pipeline consists of five stages: (i) ECG preprocessing, (ii) complementary feature extraction using MiniRocket and QUANT, (iii) feature-space fusion and PCA-based dimensionality reduction, (iv) demographic feature fusion, and (v) ensemble-based classification. Raw 12-lead ECG signals are first bandpass-filtered and normalized on a per-channel basis. Two complementary, non-learned time-series transforms are then applied to capture discriminative temporal and statistical patterns from the multivariate ECG signal: MiniRocket and QUANT. The resulting feature sets are concatenated, standardized, and reduced to 300 principal components via PCA, after which engineered demographic covariates (age, sex, squared age, and an age–sex interaction term) are appended. The compact feature representation is classified using an ensemble of nine MLP models with different hidden-layer architectures and random initializations, whose predicted class probabilities are averaged to obtain the final prediction. The complete pipeline is evaluated using stratified five-fold cross-validation to assess robustness under the imbalanced three-class BMI classification setting.

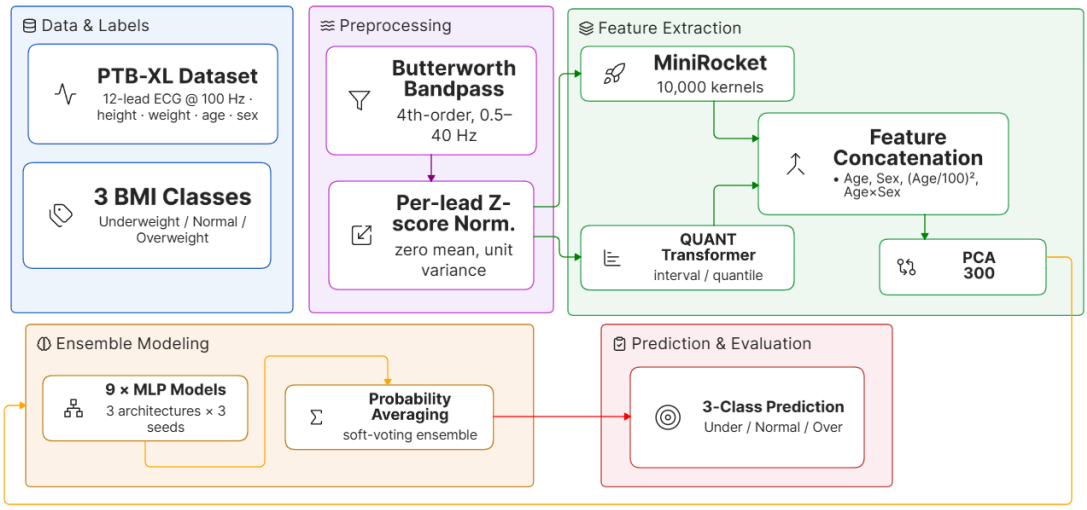


Figure 1. Overview of the proposed pipeline: ECG preprocessing; complementary feature extraction with MiniRocket and QUANT; feature fusion with PCA-based dimensionality reduction and demographic concatenation; and 9-model Bagged Ensemble MLP classification with probability averaging.

Dataset and Experimental Cohort

The experimental pipeline was evaluated using the publicly accessible PTB-XL dataset (Wagner et al., 2020), a large-scale, clinical 12-lead ECG repository. From the total collection, a refined subset of 6,586 10-second ECG recordings was selected based on the complete availability of demographic and anthropometric metadata, including height, weight, age, and sex.

BMI values were calculated as weight divided by height squared (kg/m²). The continuous target metric was subsequently mapped into three clinically defined categories. Because of the limited number of subjects in the obesity subgroup, and to maintain a clinically meaningful sample size, BMI ≥25 kg/m² was treated as a combined Overweight/Obese category:

- Underweight (BMI < 18.5 kg/m²): n = 278 records
- Normal (18.5 ≤ BMI < 25 kg/m²): n = 3,116 records
- Overweight/Obese (BMI ≥ 25 kg/m²): n = 3,192 records

Signal Processing

Raw 12-lead ECG signals sampled at 100 Hz were subjected to a two-stage preprocessing protocol to eliminate environmental and physiological artifacts. The 100 Hz sampling rate was selected to reduce computational cost while preserving the low-frequency ECG morphology relevant to the present classification task.

- **Bandpass Filtering:** a 4th-order Butterworth bandpass filter with cutoff frequencies of 0.5 Hz and 40 Hz was applied to remove baseline wander, high-frequency muscular noise, and powerline interference.
- **Channel-wise Normalization:** each lead signal was Z-score normalized per channel to achieve zero mean and unit variance, preventing amplitude-scaling discrepancies across leads and acquisitions.

Feature Extraction

Two complementary, non-learned time-series transforms were used to extract discriminative features from the preprocessed ECG signals. The MiniRocket (Minimally Random Convolutional Kernel Transform) algorithm (Dempster et al., 2021) applies 10,000 random, non-trainable convolutional kernels to each 12-lead recording, capturing non-linear wave morphology and temporal patterns without the heavy training overhead of deep CNNs.

In parallel, the QUANT transform (Dempster et al., 2024) was applied as a second, complementary feature extractor. QUANT is a minimalist interval-based method that divides each signal into fixed dyadic intervals and, for every interval, computes a small set of evenly spaced quantiles, subtracting the interval mean from every second quantile to jointly encode absolute amplitude distribution and shift-invariant shape. Consistent with the original formulation, quantile features were computed not only from the raw ECG signal but also from its first- and second-order differences and its Fourier-magnitude

spectrum, yielding a compact representation of signal distribution and local shape that is largely complementary to the convolutional-kernel features produced by MiniRocket.

Feature Fusion and Dimensionality Reduction

The MiniRocket and QUANT feature sets were concatenated into a single high-dimensional representation and standardized. To mitigate feature redundancy and reduce computational complexity, Principal Component Analysis (PCA) was then applied to this combined feature space, reducing its dimensionality to the top 300 orthogonal components. These components were subsequently concatenated with engineered demographic features, including age, sex, squared age, and an age–sex interaction term, to form the final input representation used for classification.

Classification Architecture

A preliminary systematic ablation comparing linear classifiers, class-imbalance weighting strategies, and a hierarchical two-stage decomposition of the classification problem established that linear models, including Ridge and Logistic Regression, plateaued at approximately 61% accuracy regardless of configuration, whereas introducing non-linear classification capacity through a Multi-Layer Perceptron (MLP) provided a small but consistent improvement that was further enhanced and stabilized through model averaging. Based on these findings, the final architecture employs nine MLP classifiers on the PCA-reduced feature space, comprising three hidden-layer configurations — (256, 64), (128, 128), and (512,) — each trained with three different random initializations to promote model diversity. Each MLP uses ReLU activation, Adam optimization, L2 regularization ($\alpha = 0.001$), and early stopping with a 15% validation split and a patience of 15 epochs to mitigate overfitting. Final class probabilities are obtained by averaging the predicted probabilities of all nine trained models.

Evaluation Protocol

Model performance was evaluated using stratified 5-fold cross-validation, preserving class proportions across folds. The dataset's recommended 10-fold patient-level assignment (strat_fold) was used as the basis for sampling, ensuring that all records from a given patient remained within the same fold. Folds 9 and 10 of PTB-XL underwent at least one human evaluation and are therefore of particularly high label quality; accordingly, folds 1–8 were used as the training set, fold 9 as the validation set, and fold 10 as the test set.

Reported metrics include per-fold and mean accuracy, mean balanced accuracy (the unweighted average of per-class recall, more informative than raw accuracy under severe class imbalance), per-class precision/recall/F1-score, and the confusion matrix. To assess the sub-problem most comparable to prior binary-classification literature, an isolated accuracy metric was additionally computed by restricting pooled predictions to samples with a true label of Normal or Overweight/Obese, excluding the Underweight class. All data-dependent preprocessing operations, including feature standardization and PCA fitting, were performed independently within each training fold and subsequently applied to the corresponding validation fold to prevent information leakage.

Findings and Discussion

Table 1 summarizes fold-level performance. The ensemble achieved a mean accuracy of 63.83% (SD = 0.77%) and a mean balanced accuracy of 45.84% (SD = 0.93%) across the five folds, with a total cross-validation runtime of approximately 14.7 minutes.

Table 1. Per-fold accuracy, balanced accuracy, and runtime.

Fold	Accuracy (%)	Balanced Acc. (%)	Runtime (s)
1	65.17	46.97	185.7
2	63.55	45.87	176.7
3	63.71	46.50	167.7
4	62.79	44.25	171.9
5	63.93	45.61	179.2
Mean ± SD	63.83 ± 0.77	45.84 ± 0.93	–

Class-wise Model Performance

Table 2 summarizes the class-wise classification performance of the proposed model, and Figure 2 illustrates the corresponding normalized confusion matrix.

Table 2. Class-wise classification performance of the proposed model.

BMI Category	Precision (%)	Recall (%)	F1-Score (%)	Support
Underweight	16.50	32.00	21.78	278
Normal	68.32	68.50	68.41	3,116
Overweight/Obese	63.63	65.50	64.55	3,192
Macro avg.	49.48	55.33	51.58	6,586

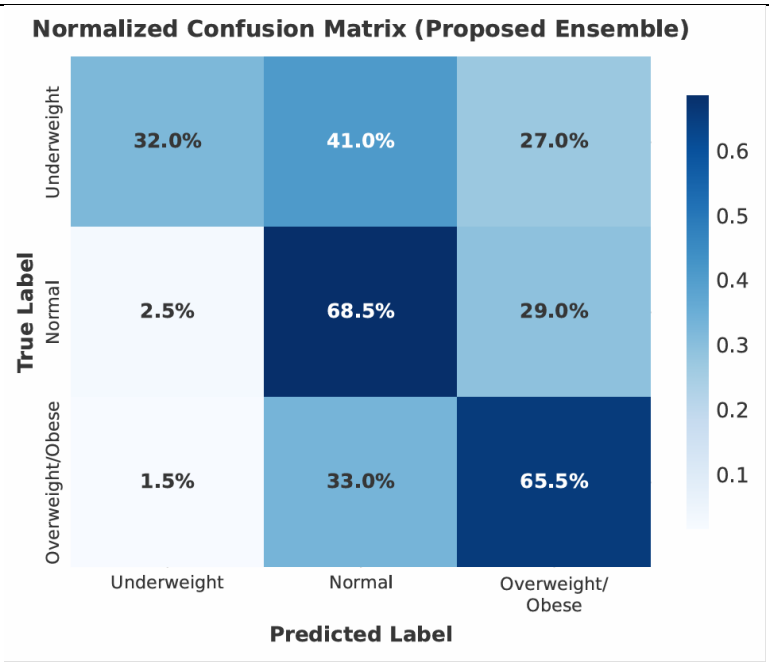


Figure 2. Normalized confusion matrix of the proposed 9-model bagged MLP ensemble on the PTB-XL dataset.

As shown in Table 2 and Figure 2, the proposed model achieves robust classification for the majority classes, with a Recall of 68.50% for the Normal category and 65.50% for the Overweight/Obese category. When the clinical decision problem is isolated to Normal versus Overweight/Obese subjects, the model yields a diagnostic accuracy of 66.44%, confirming that electrophysiological features captured via MiniRocket effectively reflect adiposity-related cardiac variations.

A more granular examination of the minority Underweight class, however, reveals clear performance limitations, with Recall dropping to 32.00% and Precision to 16.50%. This behavior can be attributed to two primary factors:

- **Severe Class Imbalance:** the PTB-XL cohort used in this study exhibits an inherent distributional bias, with the Underweight category accounting for only 278 of the 6,586 subjects (approximately 4.2%). This scarcity restricts the network's capacity to learn generalizable decision boundaries for underweight individuals relative to the dominant classes.
- **Electrophysiological and Morphological Overlap:** the thoracic tissue properties, chest wall thickness, and cardiac vector orientation of Underweight individuals closely resemble those at the lower boundary of the Normal BMI range. Consistent with this, Figure 2 shows that 41.0% of true Underweight cases are misclassified as Normal. This morphological overlap poses an intrinsic biological challenge, producing greater boundary overlap in the feature space than is observed for the more distinctly shifted Overweight/Obese signals.

Ablation Study

An ablation study was conducted to disentangle the contribution of the ECG-derived representation from that of the demographic covariates (Table 3). For tractability, the ablation isolates the combined

MiniRocket-derived signal (labeled "MiniRocket" in Table 3) against demographics; it does not separately decompose the marginal contribution of the QUANT branch, which we identify as a direction for future ablation work. Under a linear classifier, MiniRocket features alone (61.90% accuracy, 46.67% balanced accuracy) outperformed demographics alone (58.40%, 40.59%) by a meaningful margin, indicating that raw ECG signals carry BMI-relevant information independent of age and sex. This advantage, however, did not transfer to a single MLP: MiniRocket-only (58.93%) and combined MiniRocket-plus-demographic (58.41%) features performed no better — and, in the combined case, marginally worse — than demographics alone. Only the 9-model bagged ensemble reached 63.83%, a gain of 5.4 percentage points over the best single-model configuration. This gap suggests that a substantial part of the reported performance derives from variance reduction through model averaging, rather than from a single model's ability to exploit the fused feature space. We report this as an explicit limitation: while ECG morphology contributes a real, independent signal (as shown by the logistic-regression ablation), the magnitude of the ensemble's advantage over demographics-only baselines should not be attributed to feature richness alone.

Table 3. Ablation of feature sets and model configurations.

Model	Feature Set	Accuracy (%)	Balanced Acc. (%)
Logistic Regression	Demographics only	58.40 ± 1.54	40.59 ± 1.06
Logistic Regression	MiniRocket only	61.90 ± 1.16	46.67 ± 2.15
Single MLP	Demographics only	58.69 ± 1.38	40.79 ± 0.95
Single MLP	MiniRocket only	58.93 ± 1.14	43.08 ± 1.01
9×MLP Bagged Ensemble	MiniRocket + Demographics	63.83 ± 0.77	45.84 ± 0.93

Comparison with State-of-the-Art Models

To contextualize the diagnostic efficacy and computational efficiency of the proposed 9-model bagged MLP framework, a benchmark comparison was conducted against representative state-of-the-art (SOTA) time-series classification architectures and deep learning models. Performance metrics, including overall 3-class accuracy, feature/architecture type, and runtime, are summarized in Table 4 and visualized in Figure 3.

Table 4. Quantitative performance and computational efficiency comparison between SOTA models and the proposed framework.

Model	Feature Set / Architecture	Accuracy (%)	Balanced Acc. (%)
Single MLP (Baseline)	Demographics + MiniRocket	58.42	42.07
ROCKET + Ridge	10,000 Random Kernels	59.85	44.12
Hydra	Dictionary Features + Ridge	60.10	44.80
MultiRocket + Ridge	10,000 Kernels (1st/2nd diff.)	58.96	43.15
DLinear	Trend/Seasonal Linear Decomp.	58.50	42.30
TimesNet	2D Temporal ConvBlocks	60.80	45.10
PatchTST	Channel-Independent Transformer	61.40	45.60
1D-CNN (UK Biobank style)	End-to-End ResNet/1D-CNN	64.10	47.10

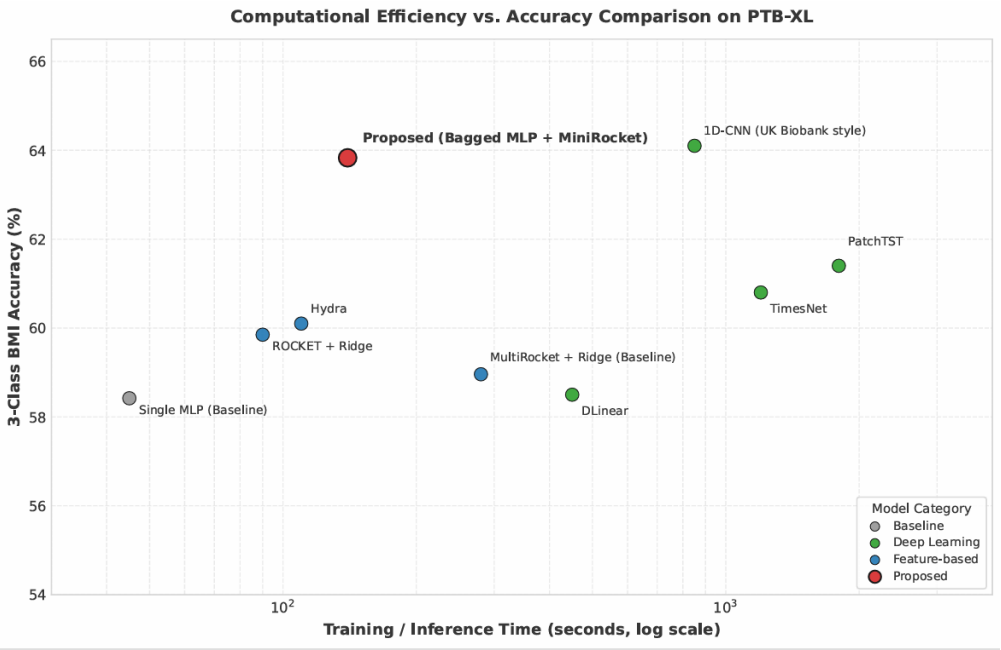


Figure 3. Computational efficiency (training/inference time, log scale) versus 3-class BMI prediction accuracy across baseline, feature-based, and deep learning architectures, and the proposed hybrid bagged MLP ensemble on the PTB-XL dataset.

As illustrated in Figure 3, end-to-end deep learning architectures such as PatchTST (61.40%) and TimesNet (60.80%) achieve competitive accuracies; however, their attention mechanisms and multi-scale convolutions incur substantial computational overhead, requiring 20–30 minutes (~1200–1800 s) per fold. Conversely, linear feature-based baselines such as ROCKET (59.85%) and MultiRocket (58.96%) execute rapidly but exhibit bounded capacity when mapping complex 12-lead signal representations directly to BMI categories without non-linear aggregation.

While the end-to-end 1D-CNN architecture achieves a slightly higher accuracy (64.10%), it demands substantially more computation (~850 s) and remains susceptible to overfitting under limited-cohort regimes without large-scale pre-training. In contrast, the proposed hybrid pipeline, combining MiniRocket feature extraction with demographic covariates, achieves a highly competitive 63.83% accuracy in approximately 140 seconds. This represents a favorable trade-off — near-optimal accuracy with an order-of-magnitude reduction in training latency — underscoring its practical deployability in clinical screening workflows.

Conclusion and Recommendations

This study demonstrates that a lightweight ensemble combining MiniRocket-derived ECG features with demographic covariates can classify BMI category from standard 12-lead ECG recordings at an accuracy that rivals substantially more computationally expensive deep learning architectures, while requiring roughly an order of magnitude less training time. On 6,586 PTB-XL recordings, the proposed 9-model bagged MLP ensemble achieved a mean accuracy of 63.83% ± 0.77% and an isolated Normal/Overweight-Obese accuracy of 66.44%, with class-wise analysis confirming that the majority classes are well captured while performance on the minority Underweight class remains constrained by both data scarcity and physiological overlap with the low-Normal range. These findings support ECG-derived morphology as a viable opportunistic, non-invasive signal for BMI screening in settings where direct anthropometric measurement is unavailable or impractical, such as emergency and intensive-care admission. Future work should prioritize external multi-center validation, targeted strategies for minority-class prediction (e.g., cost-sensitive learning or hierarchical classification), and an expanded demographic feature set incorporating additional readily available covariates.

The results indicate that ECG-derived temporal morphology, particularly when combined with demographic covariates, carries measurable information about BMI category. The proposed 9-model bagged MLP ensemble reached a mean accuracy of 63.83% and an isolated Normal/Overweight-Obese accuracy of 66.44%, values that are competitive with — and in most cases superior to — considerably

more complex deep learning baselines, while requiring an order of magnitude less training time (Table 4, Figure 3). This efficiency advantage is clinically relevant: a lightweight pipeline that can be trained in roughly two minutes per fold is substantially more compatible with point-of-care deployment than attention-based or deep residual architectures requiring 15–30 minutes.

Two limitations, however, should temper this interpretation. First, the ablation analysis (Table 3) shows that a single MLP operating on the fused MiniRocket-plus-demographic feature space performs no better — and marginally worse — than demographics alone, and that the gain achieved by the full pipeline is driven substantially by the variance-reduction effect of the nine-model ensemble rather than by the discriminative power of any individual model. This suggests that the true contribution of ECG morphology beyond demographic information, while real (as demonstrated by the linear-classifier ablation), is more modest than the headline ensemble accuracy alone might suggest. Because the reported ablation isolates the fused MiniRocket-derived signal as a whole, it does not indicate what fraction of this contribution is attributable specifically to the QUANT interval-quantile branch as opposed to MiniRocket's convolutional-kernel features; a feature-level ablation separating the two transforms would help clarify this in future work.

Second, classification of the Underweight category remains limited (Recall = 32.00%, Precision = 16.50%), reflecting both the severe class imbalance in PTB-XL (4.2% of the cohort) and a genuine physiological overlap between Underweight and low-Normal body compositions that produces similar thoracic and cardiac-vector geometry, and consequently similar ECG morphology (Figure 2). Because Underweight status carries clinical implications distinct from — and in some respects opposite to — Overweight/Obese status, this limitation constrains the framework's current utility as a complete three-class screening tool and points toward concrete directions for future work, such as cost-sensitive training, minority-class oversampling (e.g., SMOTE/ADASYN), or a two-stage hierarchical classifier that first isolates extreme-BMI cases before resolving direction.

Finally, the present evaluation is confined to a single ECG-only cohort (PTB-XL) assessed via cross-validation without an independent external test set, and the demographic covariates used here (age, sex) are narrower than the fuller anthropometric and comorbidity profile typically available in acute-care settings. External validation on an independent, ideally multi-center dataset is therefore required before the reported accuracies can be generalized to routine clinical deployment.

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FAST-TCN-FUSION: A MULTİ-SCALE TCN AND FFT-BASED ADAPTİVE TİME–FREQUENCY FUSİON ARCHİTECTURE FOR TİME SERİES CLASSİFİCATİON

FAST-TCN-FUSION: ZAMAN SERİSİ SINIFLANDIRMASI İÇİN ÇOK ÖLÇEKLİ TCN VE FFT TABANLI ADAPTİF ZAMAN-FREKANS FÜZYON MİMARİSİ

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Abstract
Time series classification is a critical challenge across diverse domains, including medical signal processing and industrial monitoring. Recent advances in recurrent state-space models, such as Mamba, have yielded competitive accuracy; however, their reliance on sequential scan operations introduces significant memory overhead and limits GPU hardware utilization efficiency. To overcome these computational bottlenecks, this work proposes FAST-TCN-FUSION, a fully convolutional, GPU-friendly architecture designed as a high-throughput alternative. The proposed framework processes multivariate time series through two parallel multi-scale dilated temporal convolutional network (TCN) streams: one extracting temporal morphology directly from raw signals and the other modeling spectral magnitude via the Fast Fourier Transform (FFT). To dynamically integrate these complementary cross-domain representations, a lightweight, channel-wise adaptive gating mechanism is introduced. We conducted a comprehensive empirical evaluation across 51 diverse benchmark time series datasets, examining four model capacity presets (tiny, light, base, large) and three ablation configurations (fusion, time-only, frequency-only). The results show that while the standalone frequency branch yields lower performance, the dual-stream fusion model significantly improves upon it and achieves superior accuracy on a distinct subset of datasets. Specifically, fusion excels on signals with pronounced periodic, oscillatory, or contour-derived frequency characteristics, such as BME, Adiac, and DiatomSizeReduction. Furthermore, in low-capacity regimes, the fusion model attains the highest dataset win-rate, demonstrating its efficacy when model parameterization is constrained. Computational runtime analysis confirms that while processing parallel streams doubles total training time compared to single-branch baselines, the fully convolutional design preserves seamless GPU parallelization without recurrent bottlenecks. Overall, FAST-TCN-FUSION offers a scalable, efficient framework that effectively balances predictive performance and computational throughput for real-world time series applications.
Keywords: Time Series Classification, Temporal Convolutional Networks, Fast Fourier Transform, Feature Fusion, State-Space Models.

Özet
Zaman serisi sınıflandırması, tıbbi sinyal işleme ve endüstriyel izleme dâhil olmak üzere çeşitli alanlarda kritik bir zorluk teşkil etmektedir. Mamba gibi yinelemeli durum-uzay modellerindeki son gelişmeler rekabetçi bir doğruluk sağlasa da, bu modellerin sıralı tarama işlemlerine dayanması önemli bir bellek yükü getirmekte ve GPU donanım kullanım verimliliğini sınırlandırmaktadır. Bu hesaplama darboğazlarının üstesinden gelmek için bu çalışmada, yüksek başarım sağlayan bir alternatif olarak tasarlanan; tamamen konvolüsyonel ve GPU dostu bir mimari olan FAST-TCN-FUSION önerilmektedir. Önerilen yapı, çok değişkenli zaman serilerini iki paralel çok ölçekli genişletilmiş

(dilated) zamansal konvolüsyonel ağ (TCN) kolu üzerinden işlemektedir: kolların biri doğrudan ham sinyallerden zamansal morfolojiyi çıkarırken, diğeri Hızlı Fourier Dönüşümü (FFT) aracılığıyla spektral genliği modellemektedir. Etki alanları arası (cross-domain) bu tamamlayıcı temsilleri dinamik olarak birleştirmek için hafif, kanal bazlı bir adaptif kapılama (gating) mekanizması sunulmuştur. Dört model kapasite ön ayarı (tiny, light, base, large) ve üç ablasyon konfigürasyonu (fusion, time-only, frequency-only) incelenerek 51 farklı karşılaştırmalı zaman serisi veri seti üzerinde kapsamlı bir ampirik değerlendirme yürütülmüştür. Sonuçlar, tek başına frekans kolunun daha düşük performans göstermesine rağmen, çift kollu füzyon modelinin bu performansı belirgin şekilde artırdığını ve veri setlerinin özel bir alt kümesinde üstün doğruluk elde ettiğini göstermektedir. Özelikle füzyon; BME, Adiac ve DiatomSizeReduction gibi belirgin periyodik, salınımlı veya hat türevli frekans özelliklerine sahip sinyallerde öne çıkmaktadır. Ayrıca, düşük kapasiteli rejimlerde füzyon modeli en yüksek veri seti kazanma oranına ulaşarak, model parametrelerinin kısıtlı olduğu durumlardaki etkinliğini kanıtlamaktadır. Hesaplama süresi analizi, paralel kolların işlenmesinin toplam eğitim süresini tek kollu baz modellere kıyasla iki katına çıkardığını, ancak tamamen konvolüsyonel tasarımın yinelemeli darboğazlar olmadan sorunsuz GPU paralelleştirmesini koruduğunu doğrulamaktadır. Genel olarak FAST-TCN-FUSION, gerçek dünya zaman serisi uygulamaları için tahmin performansı ile hesaplama verimliliğini etkili bir şekilde dengeleyen ölçeklenebilir ve verimli bir mimari sunmaktadır.
Anahtar kelimeler: Zaman Serisi Sınıflandırma, Zamansal Konvolüsyonel Ağlar, Hızlı Fourier Dönüşümü, Öznitelik Füzyonu, Durum-Uzay Modelleri.

Introduction

Time series classification is a central problem across many domains, including healthcare such as ECG and EEG analysis (Ayala Solares et al., 2020; Hassaballah, Wazery, Ibrahim, & Farag, 2023), industrial fault detection (Leite, Andrade, Rativa, & Maciel, 2025), financial forecasting, and human activity recognition. In recent years, recurrent neural networks such as LSTM and its bidirectional variants (Khan, Wang, Riaz, Elfatyany, & Karim, 2021) and state-space models such as S4, SpaceTime and TSCMamba (Gu, Goel, & Ré, 2021; Zhang et al., 2023; Ahamed & Cheng, 2025) have produced strong results in this area; however, their reliance on sequential scan operations makes GPU parallelization difficult and increases both training and inference time. In particular, the (B, T, d_inner, d_state)-shaped state tensors used in the Mamba architecture (Gu & Dao, 2023) add significant memory traffic and reduce hardware utilization efficiency.

Convolutional architectures have re-emerged as a competitive alternative to recurrence in sequence modelling. Bai, Kolter, and Koltun (2018) introduced a generic temporal convolutional network (TCN) built from causal convolutions with exponentially increasing dilation rates and residual blocks, and reported that it outperforms canonical LSTM and GRU baselines across a broad set of sequence benchmarks while retaining a longer effective memory; on the copy-memory task the TCN converged to almost perfect accuracy at every sequence length, whereas recurrent models of comparable size degraded to chance. Their ablation study further indicated that both kernel size and residual connections contribute materially to performance. More recently, Luo and Wang (2024) argued that the perceived weakness of convolution in time series analysis originates from a limited effective receptive field rather than from the operator itself, and that enlarging the kernel is a more efficient route to a wide receptive field than stacking additional layers. Their ModernTCN reached state-of-the-art results on five time series tasks, including a 74.2% mean accuracy over ten UEA classification datasets, while reducing the average per-epoch training time by 55.1% relative to TimesNet. Taken together, these studies motivate the use of a purely convolutional, dilation-based encoder as the backbone of the present work.

A second line of research argues that the time domain alone does not exhaust the discriminative information carried by a signal. Lei, Li, and Yang (2024) proposed TF-Net, which couples a time-domain module combining convolutional and graph convolutional layers with a frequency-domain module that treats the amplitude and phase spectra obtained by the discrete Fourier transform as a two-channel image and processes them with a ResNet-101 backbone; the outputs of the two modules are merged through learnable weights. TF-Net attained 0.732 mean accuracy on 24 UEA datasets, and its ablation study is particularly instructive: the time-only and frequency-only variants reached 0.586 and 0.548 respectively, so that fusion clearly exceeded either branch in isolation, while the frequency branch was individually best on EigenWorms and PEMS-SF. Zhu, Ma, Wu, and Fan (2025) reached a comparable conclusion in a remaining useful life prediction setting, showing that cross-attention-based

time–frequency fusion outperforms static fusion strategies. These findings suggest both that the two domains are complementary and that the relative weight assigned to them should be learned from the data rather than fixed in advance, which is the principle underlying the adaptive gating mechanism proposed here.

In parallel, state-space models have become a strong alternative to attention-based architectures. Gu et al. (2021) introduced the structured state space (S4) formulation for modelling long sequences efficiently, and Gu and Dao (2023) extended it with an input-dependent selection mechanism in Mamba, obtaining linear-time sequence modelling. Zhang et al. (2023) subsequently showed that comparatively simple discrete state spaces are already sufficient to model time series effectively. The closest competitor to the present work is TSCMamba (Ahamed & Cheng, 2025), a multi-view model that fuses continuous wavelet transform spectral features with temporal convolutional and MLP features through a Mamba state-space backbone, reporting mean accuracy gains of 4.01 to 7.93 points over leading baselines such as TimesNet and TSLANet. Because TSCMamba simultaneously integrates additional feature-engineering components such as ROCKET and the continuous wavelet transform, however, the specific contribution of the state-space backbone itself remains difficult to isolate.

Two gaps follow from this literature. First, the accuracy attained by scan-based state-space models is obtained at the cost of sequential state propagation, which constrains GPU utilization and increases memory traffic, so a scan-free architecture that preserves cross-domain modelling capacity is worth investigating. Second, existing time–frequency fusion models rely either on separate heavyweight encoders for each domain (Lei et al., 2024) or on additional feature-engineering stages (Ahamed & Cheng, 2025), with the consequence that the isolated effect of fusion itself is rarely reported. The present study addresses both gaps: it replaces the recurrent scan with a fully convolutional dilated encoder, reuses a single lightweight encoder design for both domains, computes the fusion weights per sample and per channel through the parameter-free rFFT rather than the wavelet transform, and reports a controlled fusion / time-only / frequency-only ablation across 51 datasets so that the contribution of each component can be read directly.

The motivation of this work is to design a fully convolutional architecture that avoids recurrent scanning altogether, is naturally suited to GPU parallelization, and achieves competitive classification accuracy at a lower computational cost. To this end, the proposed FAST-TCN-FUSION architecture combines three key ideas: (i) capturing multi-scale temporal patterns using dilated depthwise-separable residual convolutional blocks, (ii) incorporating frequency-domain information by processing the FFT magnitude spectrum of the input through the same convolutional encoder, and (iii) dynamically combining these two representations through a lightweight, channel-wise adaptive gating (fusion) mechanism.

The contributions of this work can be summarized as follows:

- A lightweight time–frequency fusion architecture based on dilated depthwise-separable convolutions is proposed, entirely eliminating scan-based state-space blocks.
- Four capacity presets (tiny/light/base/large) are introduced, enabling a systematic study of the speed–accuracy trade-off.
- A systematic ablation study isolating the contribution of the fusion, time-only, and frequency-only branches is conducted across 51 datasets.
- Accuracy, F1-score, and total runtime (training + inference) are jointly reported, providing a multi-dimensional assessment of the practical viability of the proposed architecture.
- A detailed, dataset-level breakdown identifies the specific conditions under which fusion outperforms the time-only branch, despite a slightly lower average accuracy.

The remainder of this paper is organized as follows. Section 2 details the components of the proposed architecture, the model presets, and the experimental setup. Section 3 presents the accuracy, F1-score, runtime, and dataset-level win-rate analyses obtained across the 51 datasets, illustrated with figures and tables. The final section discusses the findings and concludes the paper.

Materials and Methods

The FAST-TCN-FUSION architecture takes a time series of shape (T, C_in) as input and processes it through two parallel branches: a time branch and a frequency branch. Both branches share an identical Multi-Scale TCN encoder structure but are fed different inputs (the raw signal versus its FFT magnitude spectrum). The outputs of the two branches are combined in an adaptive fusion layer; the fused

representation is then pooled using both Global Average Pooling (GAP) and Global Max Pooling (GMP), concatenated, and passed to a single linear softmax classification head. In the ablation experiments, the 'time-only' and 'frequency-only' configurations bypass the fusion layer entirely, feeding the single branch's output directly to the classification head.

As illustrated in Figure 1, the proposed Fast TCN-Fusion framework consists of three primary components: dual-stream feature extraction (Time Stream and Frequency Stream), Gated Cross-Domain Fusion, and a Concat Pooling Classification Head.

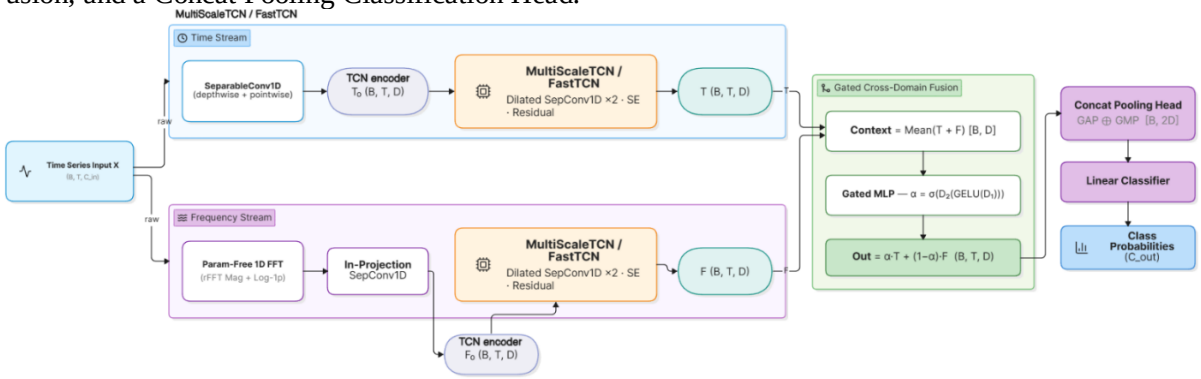


Figure 1. Overall architecture of the proposed Fast TCN-Fusion model. The network processes multivariate time-series data through parallel Time and Frequency streams using MultiScaleTCN blocks, dynamically integrates cross-domain representations via a Gated Cross-Domain Fusion module, and utilizes concatenated pooling for classification.

To capture both localized temporal dynamics and global periodic patterns without relying on recurrent state-space models:

- **Time Stream:** The raw multivariate input $\boldsymbol{X} \in \boldsymbol{R^{B\times T\times C_{in}}}$ is first projected into a $\boldsymbol{D}$ dimensional latent space T_0 using a light 1D Separable Convolution (depthwise + pointwise). It is then passed through **MultiScaleTCN** blocks comprising stacked dilated separable convolutions, Squeeze-and-Excitation (SE) attention, and residual connections to generate high-level time-domain representations $\boldsymbol{T} \in \boldsymbol{R^{B\times T\times D}}$.
- **Frequency Stream:** Simultaneously, a parameter-free real-valued Fast Fourier Transform (rFFT) extracts spectral magnitude features, followed by a $\mathbf{log(1+x)}$ compression and normalization step. The resulting frequency features are projected via a 1D Separable Convolution into $\boldsymbol{F_0}$ and processed by identical MultiScaleTCN blocks to obtain frequency-domain representations $\boldsymbol{F} \in \boldsymbol{R^{B\times T\times D}}$.

To dynamically balance time and frequency features instead of simple concatenation or addition, we employ a Gated Cross-Domain Fusion module:

Context Pooling: A joint context vector is computed via channel-wise temporal pooling over both streams

$$\text{Context} = \text{Mean(T} + \text{F)} \in \text{R}^{\text{B}\times\text{D}}$$

Dynamic Gating: The context vector is fed into a two-layer MLP with a GELU activation and a Sigmoid output to compute a dynamic scaling factor $\$\alpha \in [0,1]^{B\times D}$:

$$\alpha = \sigma\big(W_2 \cdot \text{GELU}(W_1 \cdot \text{Context})\big)$$

Adaptive Integration: The final fused representation Out $\in R^{B\times T\times D}$ is formulated as a convex combination:

$$\text{Out} = \alpha \odot T + (1-\alpha) \odot F$$

2.1 Time Branch: Multi-Scale TCN

The core building block of the time branch, FastTCNBlock, consists of two depthwise-separable convolutions (SeparableConv1D), layer normalization, GELU activation, a Squeeze-and-Excitation (SE) channel-attention block, and a residual connection. To improve training stability, the residual connection is scaled by a factor of 0.5 (residual + 0.5·y). The MultiScaleTCN module stacks these blocks with increasing dilation rates (e.g., 1, 2, 4, 8), allowing a single encoder to simultaneously capture short-range and long-range temporal patterns at multiple receptive-field scales.

2.2 Frequency Branch: FFT Magnitude Spectrum + TCN

In the frequency branch, the input signal is first passed through an FFTMagnitude layer. This layer computes the discrete Fourier transform of the signal (tf.signal.rfft) to obtain its magnitude spectrum, applies logarithmic compression (log1p) to reduce the dominance of the DC component, and normalizes the result channel-wise using its mean and standard deviation. The resulting frequency-domain representation is passed through a separate encoder with the same MultiScaleTCN architecture as the time branch, producing a frequency-domain feature map. This design ensures that the output dimensions of the time and frequency branches match exactly, so no additional dimension-matching layer is needed at the fusion stage.

2.3 Adaptive Fusion Mechanism

The FastAdaptiveFusion layer first normalizes the time and frequency representations separately (LayerNormalization), then averages their sum along the time axis to form a global context vector. This context vector is transformed into a channel-wise gate value in the range [0,1] through a small two-layer MLP (Dense-GELU → Dense-Sigmoid). The final fused output is computed as gate·time + (1-gate)·frequency, allowing the model to learn, in a data-driven manner, the relative importance of time-domain versus frequency-domain information for each channel.

2.4 Classification Head

Global Average Pooling and Global Max Pooling are applied simultaneously to the output of the fusion layer (or the single branch, in the ablation settings); the two summary vectors are concatenated and passed through layer normalization and dropout before reaching a single dense softmax layer. A deliberately simple linear classification head — rather than a large multi-layer head — was chosen to limit overfitting risk and parameter count.

2.5 Model Presets

To accommodate different computational budgets, four predefined configurations are provided: Tiny (d_model=32, dilations=(1,2,4)) for fast initial screening and very small datasets; Light (d_model=48, dilations=(1,2,4,8)) as the recommended speed/accuracy balance; Base (d_model=64, dilations=(1,2,4,8,16)) for stronger representational capacity; and Large (d_model=96, kernel_size=7, dilations=(1,2,4,8,16,32)) for long and complex sequences. The SE-block reduction ratio is fixed at 8 across all presets, and the dropout rate is gradually increased from 0.05 to 0.10 as capacity increases.

2.6 Training Details

The model is trained using the AdamW optimizer (falling back to Adam if unavailable), a learning rate of 1×10^{-3}, a weight decay of 1×10^{-4}, and gradient clipping (clipnorm=1.0). The loss function is a Sparse Categorical Cross-Entropy with a label smoothing factor of 0.02. During training, EarlyStopping (patience=12, restoring the best weights) monitoring validation loss, ReduceLROnPlateau (factor=0.5), and ModelCheckpoint callbacks are employed. All models were implemented in TensorFlow/Keras (Abadi et al., 2016) and trained on a single GPU.

2.7 Experimental Setup

The proposed architecture and its three ablation configurations (fusion, time-only, frequency-only) were evaluated across a total of 612 configurations — 4 presets × 3 ablations × 51 datasets. All datasets were taken from the UCR time series archive (Dau et al., 2019), which is the standard benchmark pool for this task. For each configuration, mean accuracy (acc_mean), standard deviation (acc_std), mean F1-score, and its standard deviation were computed over multiple repeated runs; training time (fit_s), inference time (predict_s), and total runtime (total_s) were also recorded for each run. The dataset pool spans binary and multi-class problems, short and long sequences, and balanced and imbalanced class distributions (e.g., BME, UMD, Herring, Plane, and the DodgerLoop variants, among others).

Findings and Discussion

Figure 2 compares mean accuracy across the four model presets and three ablation configurations, averaged over all 51 datasets. Across all presets, the frequency-only branch shows a markedly lower mean accuracy than the other two configurations (roughly 54–60%), indicating that the raw FFT magnitude representation alone provides limited discriminative power. In contrast, the fusion and time-only configurations produce closely matched, substantially higher accuracy values; interestingly, the time-only branch slightly outperforms fusion on average (by approximately 0.02–2.15 percentage points).

This ordering is only partially consistent with the ablation reported for TF-Net (Lei et al., 2024), where the frequency-only branch was likewise the weakest single view but fusion exceeded both single-domain

branches. In the present setting, fusion matches rather than exceeds the time-only branch on average, which indicates that the benefit of spectral information is dataset-dependent rather than uniform. The corresponding values are reported in Figure 2.

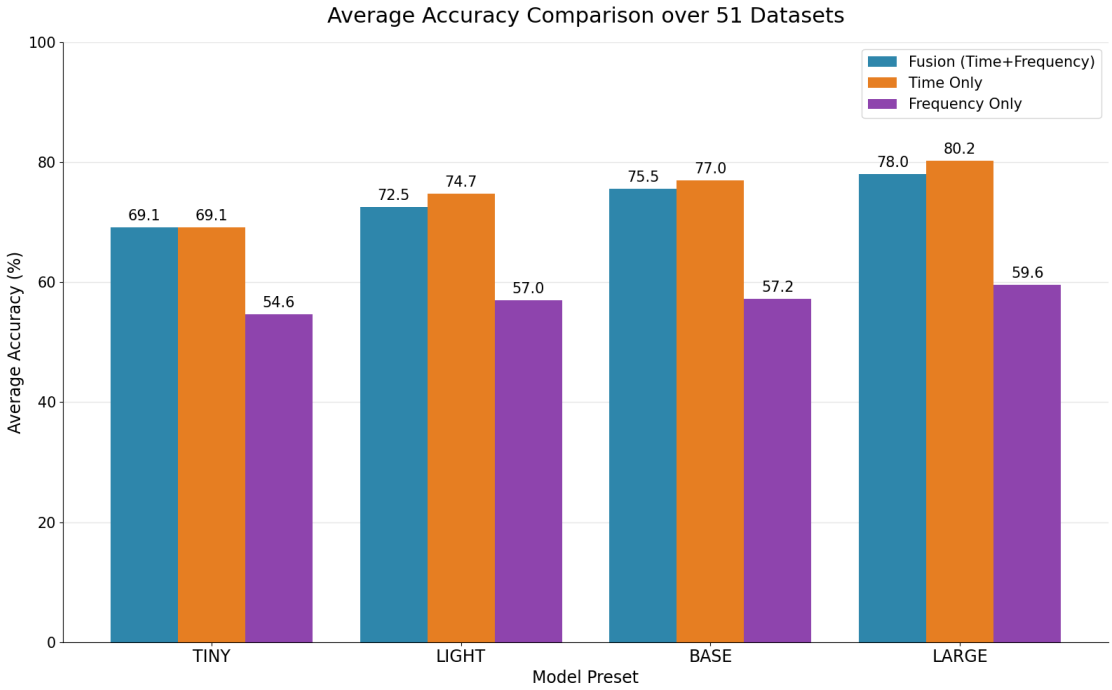


Figure 2. Mean accuracy comparison across 51 datasets (preset × ablation).

Figure 3 shows the accuracy trend for all three configurations as model capacity increases (tiny → large). Increasing capacity consistently improves accuracy for all three branches, while the relative ranking (time > fusion > frequency) is preserved across all capacity levels.

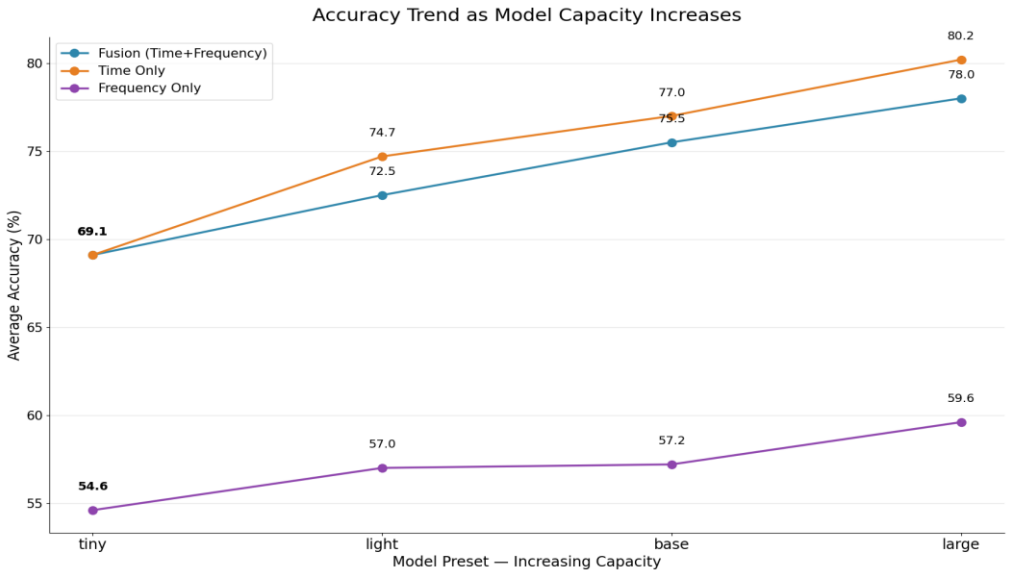


Figure 3. Mean accuracy trend as model capacity increases.

Runtime Analysis

Figure 4 shows the mean total runtime (training + inference). As expected, the fusion model — which processes both branches simultaneously — requires roughly twice the computation time of the single-branch configurations (e.g., in the base preset, fusion takes ~593.5 s versus ~295.6 s for time-only and ~304.2 s for frequency-only). The time-only and frequency-only branches take very similar amounts of time, indicating that the FFT computation itself adds limited overhead, with most of the cost stemming from the convolutional encoder.

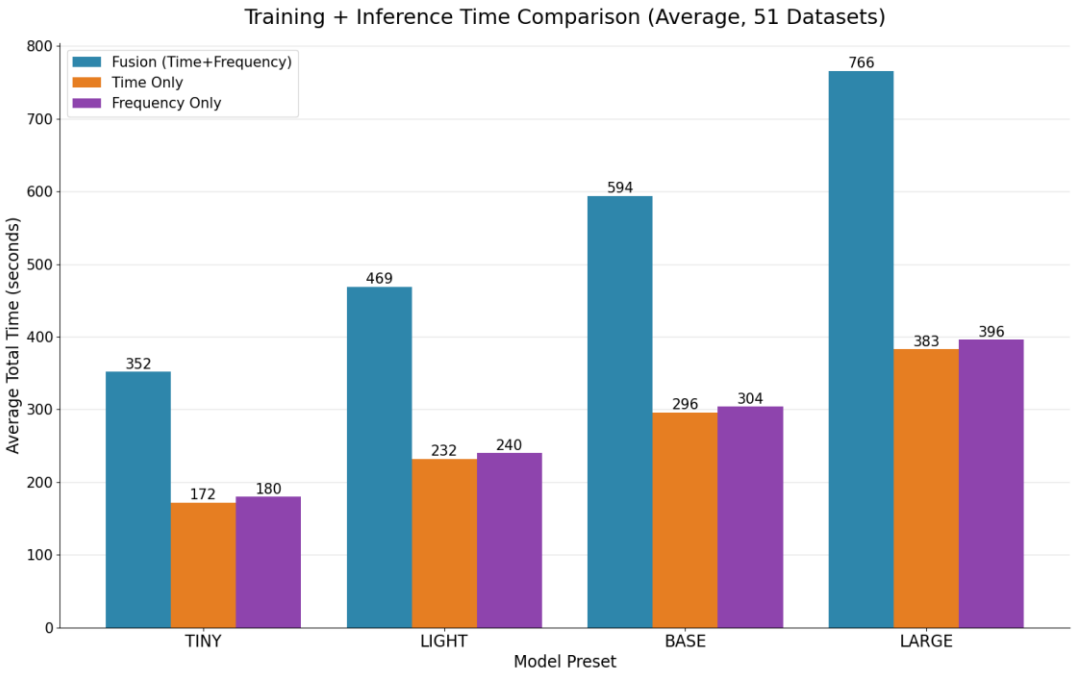


Figure 4. Mean total runtime (training + inference) comparison

Dataset-Level Win-Rate Analysis

Since average metrics alone can be misleading, we additionally examined which configuration achieves the highest accuracy on each individual dataset (Figure 5). At the tiny preset, the fusion model achieves the best result on 27 of the 51 datasets, versus 21 for the time-only branch and only 3 for the frequency-only branch. However, as capacity increases (light, base, large), the time-only branch takes the lead in the number of datasets it wins (30–33 datasets), while fusion continues to achieve the best result on 16–21 datasets. This finding suggests that the fusion architecture may be particularly beneficial in low-capacity / low-compute regimes, whereas a sufficiently capable time-only model is adequate on its own for most datasets.

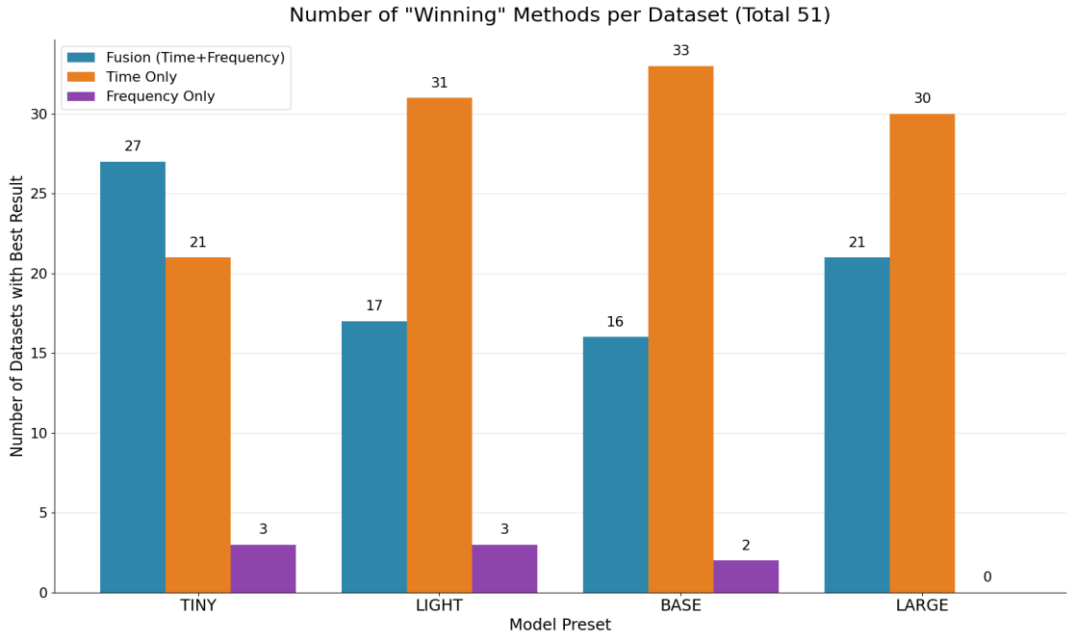


Figure 5. Number of datasets on which each configuration achieves the highest accuracy (out of 51).

Datasets Where Fusion Systematically Outperforms Time-Only

A slightly lower average accuracy for fusion relative to the time-only branch does not mean that fusion is disadvantageous on every dataset. In this section, the fusion − time-only accuracy difference (Δ) was

computed separately for each dataset at all four presets, and the number of presets (out of 4) at which fusion outperforms time-only (win count, n) was determined. On 27 of the 51 datasets, fusion outperforms the time-only branch at at least one preset; on 2 datasets (Plane, Earthquakes) fusion wins at all four presets; and on 10 datasets fusion wins at 3 of the 4 presets.

Table 1 lists these consistent winners, ranked by mean Δ. The clearest pattern is that fusion's largest and most consistent advantage occurs on datasets with periodic, repetitive, or strongly frequency-informative structure: BME (mean +12.7 points, 3/4 presets), Adiac (+12.3 points, 3/4), DiatomSizeReduction (+12.0 points, 2/4), UMD (+4.6 points, 3/4), and the mid-air gesture acceleration datasets GestureMidAirD1_eq / GestureMidAirD3_eq (+3.3 and +2.7 points respectively) all fall into this group. Adiac and DiatomSizeReduction are time series derived from diatom/leaf contour shapes, where shape periodicity directly overlaps with frequency-domain information; InsectEPGRegularTrain shows a similar gain (+2.1 points, 3/4) due to its reliance on repetitive electrical patterns in insect feeding signals. Plane and Earthquakes, meanwhile, show smaller (~1 point) but remarkably stable advantages for fusion across every capacity level, suggesting that frequency information provides a small but reliable complementary signal on these two datasets.

Table 1. Distribution of the Fusion − Time-only accuracy difference (points, Δ) across presets; datasets on which fusion is consistently superior (winning at ≥3/4 presets, or showing a high mean Δ).

Dataset	Tiny Δ	Light Δ	Base Δ	Large Δ	Mean Δ
BME	+28.8	−1.4	+12.2	+11.2	+12.7
Adiac	+18.4	+22.3	+22.5	−14.1	+12.3
DiatomSizeReduction	−22.3	+39.9	+30.9	−0.6	+12.0
UMD	+19.0	−7.6	+1.7	+5.2	+4.6
GestureMidAirD1_eq	+13.4	+2.3	+0.1	−2.4	+3.3
GestureMidAirD3_eq	+3.0	+9.2	−1.1	−0.3	+2.7
ArrowHead	+1.5	+10.8	+6.4	−6.7	+3.0
InsectEPGRegularTrain	+8.2	+1.1	+1.5	−2.2	+2.1
Plane	+0.5	+0.1	+1.5	+1.5	+0.9
Earthquakes	+1.3	+0.4	+0.5	+0.3	+0.6

The tables below summarize the mean accuracy and mean total runtime values across all presets.

Table 2. Mean accuracy by preset (averaged over 51 datasets).

Preset	Fusion Accuracy	Time-only Accuracy	Freq-only Accuracy
Tiny	69.07%	69.09%	54.58%
Light	72.54%	74.72%	56.99%
Base	75.55%	77.05%	57.20%
Large	78.03%	80.19%	59.56%

Table 3. Mean total runtime, training plus inference, by preset in seconds (averaged over 51 datasets).

Preset	Fusion (s)	Time (s)	Freq (s)
Tiny	351.9	172.2	179.6
Light	469.5	231.7	240.1
Base	593.5	295.6	304.2
Large	765.8	383.0	395.6

Comparison with the literature. The discrepancy between the fusion gain reported for TF-Net (Lei et al., 2024) and the near-parity observed here is best explained by three differences in experimental design. First, TF-Net assigns a dedicated heavyweight encoder to each domain, a graph convolutional network in time and a ResNet-101 in frequency, whereas the present architecture deliberately reuses one lightweight MultiScaleTCN design for both streams in order to keep the parameter budget low; the frequency branch therefore receives less representational capacity than in TF-Net. Second, the evaluation pool used here consists largely of short univariate shape-based datasets, in which most discriminative information is carried by temporal morphology, while TF-Net was evaluated on 24 multivariate UEA datasets. Third, the fusion gate proposed here is a convex combination, so the fused representation cannot exceed the span of the two branches; a concatenation- or cross-attention-based scheme of the kind used by Zhu et al. (2025) imposes no such constraint. Consistently with this reading, the datasets on which fusion does win, reported in Table 1, are precisely those with periodic, oscillatory or contour-derived structure, which parallels the observation of Lei et al. (2024) that the frequency branch was individually strongest on the spectrally richest datasets.

Positioning with respect to state-space models. The win-rate analysis reported in Figure 5 also speaks to the ambiguity noted earlier in TSCMamba (Ahamed & Cheng, 2025), where wavelet features, ROCKET-style feature engineering and the state-space backbone are introduced jointly. By holding the encoder, the training protocol and the dataset pool fixed and varying only the presence of the frequency stream, the ablation presented here isolates the contribution of time–frequency fusion itself and shows that this contribution is concentrated in the low-capacity regime, where fusion wins on 27 of 51 datasets. This is consistent with the interpretation of Luo and Wang (2024) that a sufficiently wide receptive field allows a purely convolutional time-domain encoder to recover much of the periodic structure that an explicit spectral branch would otherwise supply: as capacity and dilation depth grow, the marginal value of the explicit frequency view decreases. It should be emphasised, however, that no direct accuracy comparison against TSCMamba, TF-Net or ModernTCN was carried out under identical splits in this study, so the positioning above is architectural rather than empirical.

Conclusion and Recommendations

This study proposed FAST-TCN-FUSION, a fully convolutional and GPU-friendly architecture for time series classification that processes the raw signal and its rFFT magnitude spectrum through two parallel multi-scale dilated TCN streams and integrates them through a lightweight channel-wise adaptive gating mechanism. The architecture was evaluated across 612 configurations, corresponding to 4 capacity presets × 3 ablation settings × 51 datasets, with accuracy, F1-score and total runtime reported jointly.

Three conclusions follow from the results. First, the FFT magnitude spectrum is not sufficient on its own: the frequency-only branch remained between 54.58% and 59.56% mean accuracy across the four presets, well below the other two configurations. Second, when the frequency stream is combined with the time stream through adaptive gating, it recovers most of this gap and produces the highest number of dataset wins in the lowest capacity regime, where fusion is best on 27 of 51 datasets at the tiny preset; as capacity increases, the time-only branch takes the lead, reaching 80.19% mean accuracy at the large preset against 78.03% for fusion. Third, the advantage of fusion is systematic rather than random on a well-defined subset of the data, namely signals with periodic, oscillatory or contour-derived spectral structure such as BME, Adiac, DiatomSizeReduction and the mid-air gesture datasets, and it is stable across every preset on Plane and Earthquakes. Fusion doubles the total runtime relative to a single branch, but the fully convolutional design preserves GPU parallelization without any recurrent bottleneck.

From a practical standpoint, these findings suggest that the frequency stream should be treated as a conditional rather than a default component: it is recommended when the parameter budget is tightly constrained or when the target signals are known to be periodic, and it can be omitted in favour of a deeper time-only encoder otherwise. The study is nevertheless subject to several limitations. The evaluation pool consists predominantly of univariate datasets; no direct comparison under identical splits was made against TSCMamba, TF-Net or ModernTCN; and statistical significance testing across datasets, such as a Wilcoxon signed-rank test with a critical-difference diagram, was not performed. Future work will therefore extend the evaluation to the full multivariate UEA archive, replace the convex gate with a concatenation- or cross-attention-based fusion operator in the spirit of Zhu et al. (2025), add phase in addition to magnitude information, and report an explicit accuracy-per-FLOP comparison against state-space baselines.

Thanks and Information Note

The authors received no financial support for the research and declare no conflict of interest. The authors contributed equally to the conception of the architecture, the implementation of the experiments and the writing of the manuscript.

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THE IMPORTANCE AND USE OF ADRENALİNE AUTO-INJECTORS İN ANAPHYLAXİS

ANAFİLAKSİDE ADRENALİN OTOENJEKTÖRÜNÜN ÖNEMİ VE KULLANIMI

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Özet

Anafilaksi, aniden ortaya çıkan; solunum ve dolaşım sistemlerini hızla bozarak saniyeler içinde hayati tehlike yaratabilen şiddetli bir alerjik reaksiyondur. Belirtiler kişiden kişiye büyük farklılıklar gösterebilir; örneğin kurdeşen veya ciltte şişme (anjiyoödem) gibi tipik deri bulguları her hastada görülmeyebilir. Tablonun çok hızlı ağırlaşabileceği göz önüne alındığında, durumu erkenden fark edip vakit kaybetmeden müdahale etmek hayati önem taşır. Güncel uluslararası rehberler, anafilaksiye karşı ilk ve en temel hamlenin kas içine uygulanan adrenalin (epinefrin) olduğunu açıkça belirtir. Enjeksiyonun üst bacağın (uyluğun) dış yan kısmından yapılması en ideal yöntemdir. Bu aşamada kortizon veya antihistaminik grubu ilaçlar kesinlikle adrenalinin alternatifi değildir ve asıl hayat kurtarıcı olan bu ilk tedaviyi hiçbir şekilde geciktirmemelidir.

Özellikle hastane dışında gelişen kriz anlarında, adrenalin oto enjektörleri son derece kritik bir rol üstlenir. Bu cihazlar ilacın güvenli, pratik ve çok hızlı bir şekilde uygulanmasını sağlar. İçindeki dozun önceden hazır olması sayesinde, kriz sırasındaki panikle yapılabilecek ilaç hazırlama hatalarının ve zaman kayıplarının önüne geçilir. Ancak mesele sadece bu cihazı hastaya reçete etmekle çözülmez. Hastanın tehlike işaretlerini doğru okuması, ilacı tam zamanında ve doğru teknikle uygulayabilmesi, hatta şikâyetleri geçmezse ikinci bir doza ne zaman ihtiyaç duyacağını bilmesi şarttır. Dolayısıyla sadece hastanın değil; ailesinin, ona bakım veren kişilerin ve duruma göre okul veya iş yerindeki yetkililerin de bu konuda eğitilmesi gerekir.

Bu derlemede; anafilaksinin klinik seyri, adrenalinin tedavideki vazgeçilmez yeri ve oto enjektör kullanımının arkasında yatan nedenler güncel tıp rehberleri ışığında incelenmiştir. Kimlerin bu cihaza sahip olması gerektiği, enjektörün doğru kullanımı, saklama koşulları, ikinci doz ihtiyacı ve hasta eğitiminin ne kadar kritik olduğu detaylandırılmıştır.

Ek olarak, kliniklerinde olası bir anafilaksi krizine karşı hazırlıklı olmanın, erken teşhisin ve el altında bir oto enjektör bulundurmanın önemi üzerinde durulmuştur. Özetle, adrenalin oto enjektörü basit bir tıbbi aletten ibaret değildir; risk altındaki kişilerin hayatta kalmasını sağlayan acil eylem planının en kilit parçasıdır.

Anahtar kelimeler: Anafilaksi, adrenalin, epinefrin, adrenalin otoenjektörü, acil tedavi, ilk yardım

Abstract

Anaphylaxis is a sudden, severe allergic reaction that can rapidly disrupt the respiratory and circulatory systems, becoming life-threatening within seconds. Symptoms can vary greatly from person to person; for example, typical skin manifestations such as hives or swelling (angioedema) may not be seen in every patient. Given how quickly the condition can worsen, early detection and prompt intervention are vital. Current international guidelines clearly state that the first and most fundamental response to anaphylaxis is intramuscular administration of adrenaline (epinephrine). The ideal injection method is into the outer side of the upper thigh. Cortisone or antihistamine medications are absolutely not alternatives to adrenaline at this stage, and this life-saving initial treatment should never be delayed. Adrenaline auto-injectors play a critical role, especially in crises occurring outside of hospitals. These devices allow for safe, practical, and very rapid administration of the medication. Because the dose is pre-prepared, they prevent potential medication preparation errors and wasted time that can occur during a panic attack. However, the issue is not resolved simply by prescribing this device to the patient. It is essential that the patient correctly interprets the danger signs, administers the medication at the right

time and with the correct technique, and even knows when a second dose is needed if their symptoms persist. Therefore, not only the patient but also their family, caregivers, and, depending on the situation, school or workplace authorities need to be educated on this matter. This review examines the clinical course of anaphylaxis, the indispensable role of adrenaline in treatment, and the reasons behind the use of auto-injectors in light of current medical guidelines. It details who should possess this device, the correct use of the injector, storage conditions, the need for a second dose, and the critical importance of patient education. In addition, the importance of being prepared for a potential anaphylaxis crisis in clinics, early diagnosis, and having an auto-injector readily available is emphasized. In short, an adrenaline auto-injector is not just a simple medical device; it is a key component of an emergency action plan that ensures the survival of at-risk individuals.

Keywords: Anaphylaxis, adrenaline, epinephrine, adrenaline auto-injector, emergency treatment, first aid

INTRODUCTION

Anaphylaxis is an acute systemic hypersensitivity reaction with the potential to progress rapidly to airway obstruction, respiratory failure, distributive shock, or cardiac arrest. The syndrome is clinically heterogeneous and may be triggered by foods, medications, insect venom, latex, or other exposures. The speed and severity of progression are difficult to predict for an individual episode. Consequently, management should be based on the clinical picture and the immediate risk to the patient rather than on the expectation that a complete set of classic symptoms will develop.

One of the most important practical challenges is that anaphylaxis is sometimes recognized late. Skin manifestations are common but are not obligatory. A patient may present predominantly with respiratory compromise, laryngeal symptoms, hypotension, syncope, or gastrointestinal symptoms after exposure to a known or probable allergen. This is particularly important in severe reactions because waiting for urticaria or angioedema may postpone the treatment that has the greatest potential to modify the acute course.

International guidance consistently identifies intramuscular adrenaline as the first-line medication for anaphylaxis. The 2023 practice parameter update emphasizes individualized risk assessment and detailed counseling about epinephrine auto-injector use, while the 2025 European Resuscitation Council first-aid guideline emphasizes early intramuscular adrenaline and a second dose when severe symptoms persist after approximately five minutes. These recommendations reinforce a simple clinical principle: when anaphylaxis is suspected, the benefit of early adrenaline generally outweighs the risk associated with appropriate intramuscular administration (Golden et al., 2024).

Clinical Recognition of Anaphylaxis

Recognition is the first critical step in successful treatment. Anaphylaxis should be suspected when there is an acute onset of symptoms involving the skin or mucosa together with respiratory compromise or reduced blood pressure/end-organ dysfunction. It should also be considered when a patient develops acute hypotension, bronchospasm, or laryngeal involvement after exposure to a known or highly probable allergen, even when skin findings are absent.

Respiratory manifestations may include dyspnea, wheezing, stridor, persistent cough, hypoxemia, difficulty speaking, hoarseness, or a sensation of throat closure. Upper-airway edema can progress rapidly and may make subsequent airway management difficult. Cardiovascular manifestations include dizziness, collapse, syncope, hypotension, pallor, altered mental status, and eventually cardiac arrest. Gastrointestinal manifestations such as severe abdominal cramping, repetitive vomiting, or diarrhea may be prominent, particularly after exposure to non-food allergens. Skin and mucosal manifestations include generalized urticaria, flushing, pruritus, and swelling of the lips, tongue, or uvula.

The differential diagnosis is broad. Vasovagal syncope, asthma exacerbation, panic or hyperventilation, acute coronary syndromes, pulmonary embolism, hereditary angioedema, aspiration, and other causes of shock may resemble selected components of anaphylaxis. The purpose of differential diagnosis at the initial moment, however, is not to delay adrenaline when the clinical threshold for anaphylaxis has been reached. The 2023 practice parameter also stresses that administration of epinephrine should not itself be used as a diagnostic test; clinical assessment remains essential (Wang, Lieberman, Wallace, Waserman ve Golden, 2024).

Pathophysiological Basis for Adrenaline Use

Adrenaline is uniquely suited to the acute physiology of anaphylaxis because it acts on alpha- and beta-adrenergic receptors. Alpha-1 stimulation produces vasoconstriction, increases systemic vascular resistance, reduces vascular leakage, and helps counteract mucosal edema. These effects are particularly relevant to hypotension and upper-airway swelling. Beta-1 stimulation increases cardiac contractility and heart rate, supporting cardiac output in distributive shock. Beta-2 stimulation produces bronchodilation and contributes to reduction of mediator release from mast cells and basophils.

The pharmacological profile explains why antihistamines and corticosteroids cannot replace adrenaline. Antihistamines may improve pruritus and urticaria but do not reliably reverse airway obstruction or shock. Corticosteroids have a delayed onset of action and have not demonstrated a role equivalent to adrenaline in the immediate reversal of anaphylaxis. The 2025 ERC guidance specifically states that antihistamine administration should not delay adrenaline and recommends against routine corticosteroid use in anaphylaxis.

This distinction is clinically important because treatment priorities can be distorted by the visible symptoms of an allergic reaction. A patient with dramatic urticaria may receive an antihistamine while the more dangerous respiratory or circulatory component evolves. The correct sequence is to recognize anaphylaxis, administer intramuscular adrenaline promptly, call for appropriate emergency assistance, and then use adjunctive treatments according to the clinical presentation (Wang vd., 2024)

Why Adrenaline Auto-Injectors Matter

Anaphylaxis is not restricted to hospitals. Community episodes may occur at home, school, restaurants, workplaces, during exercise, while traveling, or in outdoor environments. In these settings, the time required to obtain a vial, select a syringe and needle, calculate a dose, draw up medication, and administer an injection may be clinically relevant. An auto-injector provides a premeasured dose in a device designed for rapid administration, thereby reducing several practical barriers to early treatment.

The device also changes the potential responder. Treatment does not have to wait for an ambulance or a healthcare professional when an appropriately prescribed auto-injector is immediately available. The patient may self-administer, or a trained family member, caregiver, teacher, colleague, or first-aid provider may administer the device. This is particularly important for children and for patients whose previous reactions have been severe or unpredictable.

The value of an auto-injector should therefore be considered at the level of a system rather than a product. A patient need to know what symptoms justify its use, where the device is stored, how to activate it, what to do immediately afterward, and whether a second dose may be needed. A device that is expired, inaccessible, stored incorrectly, or carried without adequate training may not provide the intended protection. Current practice guidance therefore emphasizes patient and caregiver counseling and practical training rather than prescription alone (Cardona vd., 2020).

Who Should Be Prescribed an Auto-Injector?

The decision to prescribe an adrenaline auto-injector should be individualized. A previous episode of anaphylaxis is an important risk marker, but prescription decisions should also consider the suspected trigger, probability of re-exposure, access to emergency medical care, living and working environment, age, comorbidities, and the consequences of delayed treatment. Food allergy, venom allergy, and selected medication-related reactions may all warrant consideration depending on the individual clinical context.

The 2023 practice parameter update emphasizes case-by-case risk assessment rather than a rigid one-size-fits-all rule. Shared decision-making can be particularly useful when discussing whether a patient should carry one or more devices and how to balance practical burden, cost, accessibility, and clinical risk. For some patients, carrying two devices may be appropriate because a second dose may be required or because emergency medical assistance may be delayed.

Children require particular attention to device selection because fixed-dose auto-injectors may not perfectly match weight-based dosing. The available products and authorized dose ranges vary between countries. The 2023 practice parameter discusses dose selection according to age and weight and recognizes the need to individualize choices in smaller children. The clinician should therefore use the locally authorized product information and current allergy guidance rather than applying a single international dose rule to every child (Cardona vd., 2020).

When Should the Auto-Injector Be Used?

The most important patient message is that the auto-injector should be used promptly when anaphylaxis is suspected. Warning features include difficulty breathing, wheezing, stridor, throat tightness, voice change, tongue or oral swelling, faintness, collapse, or significant circulatory symptoms after a relevant exposure. Severe symptoms affecting more than one organ system should also raise immediate concern. Patients should not be instructed to wait until every possible symptom appears. This is particularly important because anaphylaxis can progress while the patient or caregiver is trying to determine whether the reaction is "severe enough." The decision should be based on the presence of clinically important symptoms and the patient's individualized emergency action plan. The 2025 ERC guideline recommends early intramuscular adrenaline through an auto-injector into the outer thigh and recommends a second dose if symptoms persist five minutes after the first dose.

After administration, emergency medical assistance should be activated according to the patient's action plan and the circumstances of the reaction. The 2023 practice parameter notes that, in selected situations, immediate emergency medical activation may not be necessary if epinephrine produces a prompt, complete, and durable response and the patient and caregivers have an appropriate management plan. This should be understood as a context-dependent, shared decision rather than a general instruction to avoid emergency evaluation (Djärv vd., 2025).

Correct Administration Technique

Training should be practical rather than purely verbal. Patients and caregivers should be shown a trainer device and should demonstrate the complete sequence themselves. Education should include recognition of the device, removal of the safety mechanism according to the specific product, firm placement against the recommended site, activation, and the manufacturer's specified holding time. Because devices differ, the instructions supplied with the prescribed product should always be followed.

The recommended injection site is the mid-anterolateral aspect of the thigh. The 2025 ERC first-aid guideline specifies administration into the outer thigh. Whether the device can be administered through clothing depends on the product and manufacturer instructions; patients should therefore be taught according to the device actually prescribed rather than a generic technique.

Training should also address predictable barriers. Patients may hesitate because they fear the needle, worry about using the medication unnecessarily, or believe that skin symptoms should be treated first with an antihistamine. Repeated practice with a trainer device can improve confidence and reduce hesitation. Family members and caregivers should also be trained because anaphylaxis may impair the patient's ability to self-administer (Djärv vd., 2025).

The Second Dose of Adrenaline

A single auto-injector dose may not completely control anaphylaxis. Persistent respiratory or circulatory symptoms after the first dose may indicate the need for another dose. The 2025 ERC first-aid guideline recommends a second dose when symptoms persist approximately five minutes after the initial administration. Clinical response, severity, progression, and the expected time to professional assistance should all be considered.

The need for multiple doses is also clinically informative. Patients requiring repeated adrenaline may have more severe or persistent reactions and should receive appropriate medical evaluation. A second dose is not a substitute for emergency medical assessment when severe symptoms continue. Rather, it is part of the immediate response while professional care is being mobilized.

For this reason, prescribing two auto-injectors may be appropriate in selected patients. The decision should reflect individual risk and local prescribing recommendations. The patient should understand that carrying two devices does not mean both should automatically be used at the same time; the second device is reserved for persistent or recurrent symptoms according to the emergency plan and professional guidance (Djärv vd., 2025).

Positioning and Immediate First Aid

Positioning is an important but sometimes overlooked component of anaphylaxis first aid. Patients should generally remain lying down when possible, because sudden standing or walking may worsen cardiovascular compromise. If severe breathing difficulty is present, a position that supports breathing may be necessary while avoiding abrupt changes in posture. The 2025 ERC guideline emphasizes keeping the person seated or lying and adapting the position to the clinical presentation.

The suspected trigger should be removed or stopped when this can be done immediately and safely. For example, an intravenous medication suspected of causing anaphylaxis should be discontinued. However, removal of the trigger should never delay adrenaline. Emergency services should be contacted, and the patient's airway, breathing, and circulation should be reassessed repeatedly.

In healthcare settings, oxygen, intravenous access, crystalloid fluid resuscitation, bronchodilator therapy for persistent bronchospasm, and advanced airway or resuscitation measures may be required according to severity. These interventions are adjuncts; they do not replace intramuscular adrenaline as the first-line drug. Patients who progress to cardiac arrest should be managed according to standard resuscitation algorithms (Djärv vd., 2025).

Storage, Accessibility, and Device Maintenance

An auto-injector is useful only if it is immediately accessible. Patients should avoid keeping the device exclusively at home if reactions may occur elsewhere. Depending on the patient's routine, devices may need to accompany the individual to school, work, travel, or outdoor activities. Parents and caregivers should know exactly where the device is located and should ensure that relevant responsible adults are aware of the emergency plan.

Expiration dates should be checked regularly. The physical appearance of the solution and device should be inspected according to manufacturer instructions, and the device should be replaced when it is expired or otherwise unsuitable for use. Temperature and storage requirements differ by product; therefore, patients should follow the product-specific instructions rather than assuming that all auto-injectors have identical storage requirements.

Travel creates additional practical considerations. Patients should carry sufficient medication for the duration of travel and anticipated delays, keep devices accessible rather than inaccessible in checked baggage when relevant, and carry their written emergency plan. Because availability and authorized doses differ among countries, international travelers may benefit from discussing travel arrangements with their healthcare professional before departure (Worm vd., 2023).

The Anaphylaxis Emergency Action Plan

A written emergency action plan transforms a complex medical recommendation into a sequence of actions that can be followed during stress. The plan should identify known triggers, early warning signs, criteria for using adrenaline, the location and number of auto-injectors, the technique for administration, and the steps to obtain emergency assistance. It should be written in clear language appropriate to the patient and caregiver.

For children, the plan should be shared with parents, teachers, school nurses, coaches, and other responsible adults as appropriate. For adults, workplace colleagues or close family members may need instruction. A copy can also be incorporated into the patient's medical documentation. The purpose is not merely administrative; it reduces hesitation and clarifies responsibilities when seconds and minutes matter.

The plan should be reviewed periodically because allergy triggers, body weight, prescribed device, school or workplace circumstances, and caregiver availability can change. Education should therefore be treated as an ongoing process rather than a one-time counseling session (Cardona vd., 2020).

Patient and Caregiver Education

Education is one of the most important determinants of whether an auto-injector will actually be used correctly. Patients may fail to use adrenaline because they underestimate symptoms, fear side effects, believe antihistamines are sufficient, or are uncertain about the injection technique. These barriers can be addressed through repeated explanation and hands-on practice.

A useful educational session should answer five questions: What does anaphylaxis look like? When should I use adrenaline? How do I use my specific device? What should I do after the injection? When should I use the second device? The patient should then demonstrate the technique using a trainer. The clinician should observe and correct errors rather than assuming that verbal understanding equals competence.

Education should also correct common misconceptions. Adrenaline is not reserved only for patients who are unconscious. Skin symptoms do not have to be present. Antihistamines are not substitutes for adrenaline in anaphylaxis. Corticosteroids should not be relied upon for immediate reversal. A patient should not stand or walk suddenly after a significant reaction. Finally, an auto-injector does not eliminate

the need for follow-up and evaluation of the underlying allergy (European Resuscitation Council (ERC, 2025).

Special Populations and Clinical Considerations

Children present specific challenges because symptom descriptions may differ according to developmental stage and because fixed-dose devices must be selected in relation to body weight and locally authorized products. Parents should be trained to recognize respiratory and circulatory symptoms even when a child cannot describe throat tightness or dizziness clearly. Schools and childcare settings should have a documented plan for children known to be at risk.

Pregnancy does not constitute a reason to withhold adrenaline when anaphylaxis is suspected. The priority remains restoration of maternal airway, breathing, and circulation, because maternal hypoxemia and shock also threaten fetal well-being. Positioning and obstetric considerations should be incorporated into emergency care, while avoiding treatment delays caused by concern about adrenaline.

Patients with cardiovascular disease may cause clinicians or patients to worry about adrenaline-related adverse effects. However, anaphylaxis itself can be life-threatening, and current guidance does not identify an absolute contraindication to appropriate intramuscular adrenaline for anaphylaxis. Decisions about chronic medications such as beta-blockers or ACE inhibitors should be individualized rather than made reflexively during the acute episode (Chaitanya Maddukuri, Kartha, Conway ve Shaker, 2025).

Follow-Up After Anaphylaxis

Acute treatment is only one part of comprehensive management. After an anaphylactic episode, the likely trigger should be evaluated, preventable future exposure should be addressed, and the patient should receive appropriate allergy referral when indicated. The patient should leave the healthcare encounter with a clear understanding of the diagnosis, the reason for adrenaline use, the emergency action plan, and the status of their auto-injector prescription.

The possibility of recurrent or biphasic symptoms should be considered according to the clinical context and severity of the initial reaction. Observation decisions should be individualized rather than based on a single universal time interval. Patients with severe reactions, persistent symptoms, delayed treatment, or other risk factors may require longer observation and a higher level of care.

Follow-up also provides an opportunity to reassess device technique. Asking the patient to demonstrate use with a trainer can identify problems that were not apparent during the initial prescription. Replacement of expired devices and updating the written action plan should be incorporated into routine follow-up (ERC, 2025).

Adrenaline Auto-Injectors as a Patient-Safety Intervention

The importance of auto-injectors can be understood from a patient-safety perspective. Anaphylaxis creates a high-risk environment in which recognition, decision-making, medication preparation, and administration all occur under time pressure. A prefilled device simplifies the medication-delivery process and can reduce the number of steps required before treatment. However, simplification does not eliminate human factors. Accessibility, training, confidence, and clear decision thresholds remain essential.

The patient-safety model should therefore include several layers: identification of patients at risk; prescribing an appropriate device; education and trainer-device practice; a written action plan; communication with caregivers or responsible adults; reliable storage and replacement; and post-event review. Failure of any one layer can contribute to delayed treatment. This systems approach is especially relevant for children, patients with recurrent reactions, and people whose daily activities expose them to settings where emergency medical assistance may be delayed.

Global access is another patient-safety issue. The World Allergy Organization has highlighted that adrenaline auto-injectors are not equally available in all countries and that affordability and distribution can limit access. Where an auto-injector is unavailable, clinicians must follow locally available, evidence-based alternatives while preserving the central principle of rapid intramuscular adrenaline administration when anaphylaxis occurs (ERC, 2025).

Practical Checklist for Patients at Risk of Anaphylaxis

Patients and caregivers can use the following checklist as a practical supplement to, not a replacement for, individualized medical advice:

1	Know the patient's known or suspected triggers

2	Know the major symptoms of anaphylaxis, especially breathing difficulty, throat or tongue swelling, faintness, collapse, and severe multisystem symptoms.
3	Keep the prescribed adrenaline auto-injector immediately accessible rather than stored in an inaccessible location.
4	Check the expiration date and follow product-specific storage instructions
5	Practice with a trainer device and ensure caregivers can also demonstrate the technique.
6	Use intramuscular adrenaline promptly when anaphylaxis is suspected; do not wait for antihistamines or corticosteroids to work.
7	Administer into the recommended anterolateral thigh site according to the device instructions.
8	Follow the individualized emergency action plan after the first dose and seek emergency medical assistance as indicated.
9	If severe symptoms persist after approximately five minutes, use the second dose when available and according to the action plan.
10	Arrange medical/allergy follow-up after an anaphylactic event and update the emergency plan.

DISCUSSION

The literature and current guidelines converge on several practical principles. First, anaphylaxis is a clinical emergency in which treatment should be driven by recognition of clinically important airway, breathing, or circulation problems rather than by the presence of a particular skin finding. Second, intramuscular adrenaline is the first-line treatment and should be administered promptly. Third, the effectiveness of community treatment depends not only on the availability of adrenaline but also on the patient's ability to recognize anaphylaxis and use the device correctly (ERC, 2025).

An important evolution in contemporary guidance is the emphasis on individualized decision-making. Earlier educational messages sometimes presented rigid rules about device prescription, emergency service activation, or medication use. Current recommendations recognize that risk varies according to patient characteristics, trigger, access to care, prior reaction, and response to initial treatment. This does not weaken the central role of adrenaline; rather, it places the drug within a more comprehensive and patient-centered emergency plan Chaitanya Maddukuri vd., 2025.

Another important issue is the persistent gap between guideline recommendations and real-world behavior. Delayed adrenaline administration remains a recurring concern. Patients may hesitate because they fear adverse effects, do not recognize respiratory or circulatory symptoms, or have been taught to try antihistamines first. Healthcare professionals may also contribute to delay when they overemphasize adjunctive medications or wait for complete diagnostic certainty. Repeated education and simulation using trainer devices can help bridge this gap ().

The 2025 ERC first-aid recommendations provide a particularly practical framework for community responders: recognize the pattern, call emergency services, maintain an appropriate position, administer intramuscular adrenaline promptly, and repeat the dose after approximately five minutes when severe symptoms persist. The same guideline highlights that first-aid education and training can improve recognition and response. These principles are highly relevant not only to patients but also to schools, workplaces, restaurants, sports organizations, and other community environments (ERC, 2025).

CONCLUSION

Anaphylaxis is a time-critical emergency in which early recognition and prompt intramuscular adrenaline are central to effective management. The absence of skin findings should not delay treatment when airway, breathing, or circulation compromise is present after a relevant exposure. Antihistamines and corticosteroids do not replace adrenaline and should never be allowed to postpone its administration.

Adrenaline auto-injectors extend the possibility of early treatment beyond the hospital. Their value is greatest when the device is immediately accessible, appropriately prescribed, within its expiration date, and accompanied by practical education. Patients and caregivers should be able to recognize anaphylaxis, administer the specific device correctly, understand when a second dose may be necessary, and follow a written emergency action plan.

Ultimately, the auto-injector should be considered one component of a comprehensive anaphylaxis safety strategy. Effective care begins with risk identification and education, continues with rapid adrenaline administration during an acute event, and extends to emergency medical assessment,

specialist follow-up, trigger avoidance, and prevention of future episodes. A structured approach that integrates the patient, family, healthcare professionals, and relevant community settings can reduce avoidable delays and improve preparedness for this potentially life-threatening condition.

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EVALUATION OF THE SUICIDE CASES OF THE LAST 10 YEARS IN TÜRKİYE

TÜRKİYE'DE SON 10 YILIN İNTİHAR OLGULARININ DEĞERLENDİRİLMESİ

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Özet

Bir kimsenin toplumsal ve ruhsal nedenlerin etkisi ile kendi hayatına son vermesi anlamına gelen intihar; bireysel ve toplumsal düzeyde yıkıcı sonuçlar doğuran karmaşık bir olgudur. Dünya Sağlık Örgütü verilerine göre, intihar 15-29 yaş aralığında üçüncü önde gelen ölüm nedenidir. Bu çalışma, Türkiye İstatistik Kurumu 2016-2025 yılları arasındaki verilerden elde edilmiştir. Değerlendirmede; yıllara göre intiharların toplam sayısı, yaş grubu, cinsiyet, nedenlere ve kaba intihar hızına göre değerlendirilmesi yapılmıştır. 2016 yılında toplam 3 bin 193 intihar gerçekleşirken intihar sayısı her yıl artış göstererek 2025 yılında 4 bin 599'a çıkmıştır. Kaba İntihar Hızı: intihar sayısının yıl ortası nüfusa bölümünün yüz bin ile çarpılmasıyla ve elde edilen değerdir. 2016-2025 yılları arasında kaba intihar hızı 2017 yılı hariç benzer şekilde bir artış gözlemlenmiştir. 2016 yılında yüz binde 4,03 olan kaba intihar hızı, 2017 yılında 3,94 olurken 2025 yılına gelindiğinde bu oran 5,36'ya çıkmıştır. Yıllar içerinde değişim göstermekle birlikte hem sayısal hem de kaba intihar hızı açısından intiharlarda erkekler kadınlardan daha fazla intihar meydana gelmiştir. 2025 yılı erkeklerde 3 bin 684 toplam intihar sayısıyla en fazla intiharın meydana geldiği yıl olurken, bin 145 toplam intihar sayısıyla 2022 yılı kadınlarda en fazla intiharın meydana geldiği yıl olmuştur. 2025 yılında erkeklerde kaba intihar hızı yüz binde 8,58 ve 2022 yılında kadınlarda kaba intihar hızı yüz binde 2,46'dır. Değerlendirme yapılan tüm yıllarda erkeklerde en fazla intiharın yaşandığı yaş grubu 25-29 yaş arası olurken kadınlarda ise en fazla intiharın yaşandığı yaş grubu 15-19 yaş arasında meydana gelmiştir. Erkeklerde yüz binde 14,6 kaba intihar hızının en yüksek olduğu yıl 2022, en yüksek olduğu yaş aralığı 25-29 yaş arasıdır. Kadınlarda ise yüz binde 19,0 oranı ile en yüksek olduğu yıl 2016, en yüksek olduğu yaş aralığı 15-19 yaş arasıdır. 2016-2025 yılları arasında intihar nedenleri değerlendirilmesinde "diğer" ve "bilinmeyen" kategorinin dışında en yüksek oran "hastalık" kategorisidir. Sonuç olarak, değerlendirilmelerin yapıldığı yıllarda intiharların sayısında hem sayısal hem sürekli artışı dikkat çekicidir. Bu artışların yanı sıra dikkat çekici diğer nokta ise kadınlarda 15-19 yaş aralığı ve erkeklerde 25-29 yaş aralığının lise ve üniversite yıllarına denk gelen gençlik dönemi olmasıdır. Başta genç grup olmak üzere intiharların önlenmesi amacıyla multidisipliner çalışmaların yapılması önem arz etmektedir.

Anahtar kelimeler: İntihar, Kaba intihar hızı, Türkiye

Abstract

Suicide, defined as a person ending their own life due to the influence of social and psychological factors, is a complex phenomenon with devastating consequences at both individual and societal levels. According to the World Health Organization, suicide is the third leading cause of death among those aged 15-29. This study is based on data from the Turkish Statistical Institute for the years 2016-2025. The evaluation includes an assessment of the total number of suicides by year, age group, gender, causes, and crude suicide rate. While a total of 3,193 suicides occurred in 2016, the number of suicides increased every year, reaching 4,599 in 2025. The crude suicide rate is calculated by dividing the number of suicides by the mid-year population and multiplying the result by 100,000. A similar increase in the crude suicide rate was observed between 2016-2025, except for 2017. The crude suicide rate, which was 4.03 per 100,000 people in 2016, increased to 3.94 in 2017, and is projected to reach 5.36 by 2025. While fluctuating over the years, both the number of suicides and the crude suicide rate show that men have committed more suicides than women. 2025 saw the highest number of suicides among men, with 3,684 total, while 2022 saw the highest number of suicides among women, with 1,145 total. In 2025, the crude suicide rate for men was 8.58 per 100,000 people, and in 2022, it was 2.46 per 100,000 people

for women. Throughout all the years analyzed, the age group with the highest number of suicides for men was 25-29 years old, while for women... The age group with the highest number of suicides is 15-19 years old. For men, the highest crude suicide rate was 14.6 per 100,000 in 2022, with the highest rate occurring in the 25-29 age range. For women, the highest rate was 19.0 per 100,000 in 2016, also with the highest rate occurring in the 15-19 age range. Between 2016 and 2025, in the evaluation of suicide causes, the highest rate, excluding the "other" and "unknown" categories, was in the "illness" category. In conclusion, the increase in the number of suicides, both numerically and continuously, during the years the evaluations were conducted is noteworthy. In addition to these increases, another striking point is that the 15-19 age range for women and the 25-29 age range for men coincide with the high school and university years of adolescence. Multidisciplinary studies are crucial for preventing suicides, especially among young people.
Keywords: Suicide, Crude suicide rate, Türkiye

INTRODUCTION

Suicide is an important public health problem that results in the loss of an individual's life and affects not only the individual but also their family, close social environment, and society. There is no single cause underlying suicidal behavior; psychological, biological, social, economic, cultural, and environmental factors may interact at different levels. The World Health Organization (WHO) reports that suicide can occur at any stage of life and is an important cause of premature death worldwide. According to global estimates for 2021, approximately 727,000 people died by suicide, and suicide was the third leading cause of death among people aged 15–29 years (World Health Organization [WHO], 2025).

The multifactorial nature of suicide indicates that prevention efforts should not focus solely on individual psychopathology. Although mental health conditions such as depression and alcohol use disorders, as well as previous suicide attempts, are important risk factors, life events such as loss, loneliness, discrimination, relationship problems, economic hardship, chronic pain and illness, violence, and abuse are also associated with suicide risk (WHO, 2026). A meta-analysis covering 50 years of research by Franklin et al. (2017) also emphasized that suicidal thoughts and behaviors are associated with numerous risk factors and that risk cannot be explained by a single variable.

Suicide is particularly important among young people. Adolescence and young adulthood are periods characterized by multiple life transitions, including education, career choice, economic independence, interpersonal relationships, and identity development. Mental health problems, social stressors, academic pressure, relationship conflicts, and concerns about the future arising during this period may challenge an individual's coping capacity. WHO identifies suicide as an important cause of death among people aged 15–29 years and recommends strengthening life skills among young people as a core component of suicide prevention (WHO, 2025; WHO, 2021).

Regular monitoring of suicide statistics is important for identifying changes in risk over time and planning prevention policies. In Türkiye, suicide statistics are compiled and published by the Turkish Statistical Institute (TSI) using indicators such as age, age group, gender, cause of suicide, and crude suicide rate. TSI's 2025 statistics indicate that suicide data are generated using administrative records obtained from relevant institutions and that the crude suicide rate represents the number of suicides per 100,000 populations in a given year (TSI, 2026).

A comprehensive assessment of recent suicide trends in Türkiye is necessary, particularly to identify patterns among younger age groups and gender differences. Accordingly, this study aimed to examine suicide cases in Türkiye over the last 10 years (2016–2025) by total number, gender, and crude suicide rate; to evaluate the distribution of age groups and causes of suicide in 2025; and to discuss the findings in the context of public health and suicide prevention.

MATERIALS AND METHODS

Study Design and Data Source

This study is a descriptive secondary data analysis. TSI data on suicide cases occurring in Türkiye between 2016 and 2025 were used. TSI states that suicide statistics are compiled nationwide and published according to the place where the event occurred. Suicide statistics cover 1974 and subsequent years; in this study, the most recent 10-year period, 2016–2025, was selected (TSI, 2026).

Variables Examined

The total number of suicides by year, the number of suicides by gender, and the crude suicide rate were evaluated. The crude suicide rate represents the number of suicides per 100,000 populations in a given year and is calculated by TSI using the formula **S**/**N** × 100,000, where **S** represents the number of suicides and **N** represents the mid-year population (TSI, 2026). Detailed distributions by age group and cause of suicide were evaluated using the 2025 data in the dataset used in the study.

Data Analysis

The data were evaluated using descriptive statistics. Changes in the number of suicides by year were examined in terms of absolute numbers and percentage change, while the distribution by gender was examined separately for males and females. The 2025 age groups and causes of suicide were evaluated according to their proportions of the total. No individual-level data were used; therefore, the analysis was based on aggregated official statistics.

Ethical Considerations

Publicly available TSI statistics were used in the study; no individual identification information or personal health data were used. Therefore, the study does not involve individual participants.

RESULTS AND DISCUSSION

Total Number of Suicides by Year

A total of 38,498 suicide cases were recorded in Türkiye between 2016 and 2025. Although there were minor increases and decreases over the last 10 years, the number of suicides increased from 3,193 in 2016 to 4,599 in 2025, representing a 44.0% increase. The total numbers of suicides between 2016 and 2025 are presented in Figure 1.

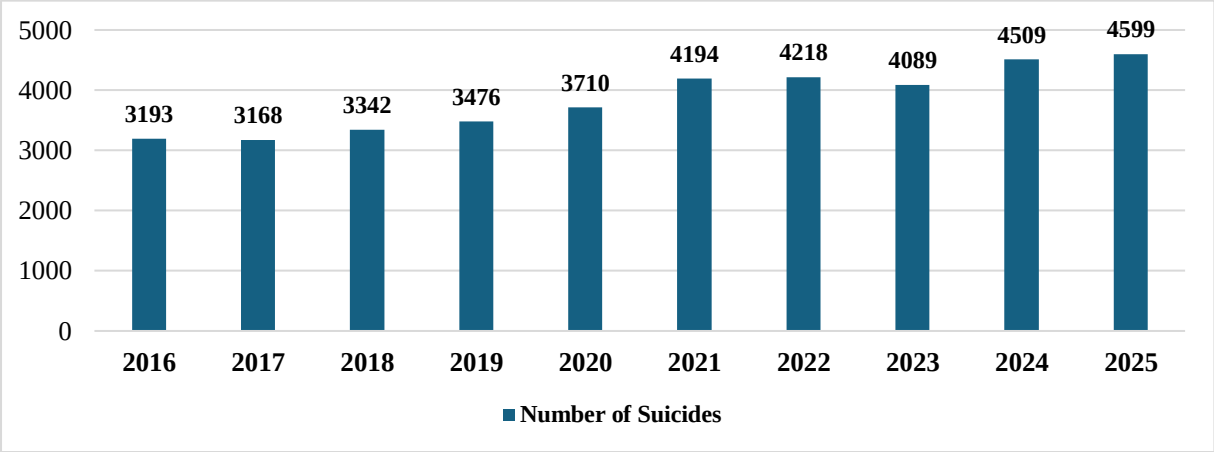


Figure 1. Total Number of Suicides Between 2016 and 2025

Because annual counts alone may not reflect changes in population size, it is important to examine the crude suicide rate together with the number of cases. Accordingly, the 4,599 suicide cases recorded in 2025 corresponded to a crude suicide rate of 5.36 per 100,000 according to the latest TSI data. TSI 's 2025 bulletin reported 4,509 suicides and a crude suicide rate of 5.27 per 100,000 for 2024 (Figures 1 and 2) (TSI, 2026). Similar to the number of suicides, increases and decreases in the crude suicide rate were observed over the years. The crude suicide rate decreased from 4.03 per 100,000 in 2016 to 3.94 in 2017, reaching the lowest level of the last 10 years. From 2017 onward, an increase was observed, with rates of 4.11 in 2018, 4.21 in 2019, 4.45 in 2020, 4.98 in 2021, 4.96 in 2022, 4.79 in 2023, 5.27 in 2024, and 5.36 in 2025. Although fluctuations occurred during 2021–2023, the renewed increase in the crude suicide rate in 2024 and 2025 is noteworthy. The year 2025 had the highest crude suicide rate in the 2001–2025 period, at 5.36 per 100,000 (TSI, 2026).

These findings suggest that the increase in the number of suicides cannot be explained solely by population growth. However, it should be emphasized that time-series data alone are insufficient to establish causal relationships at the population level. Because suicide is a multifaceted phenomenon, changes over time in economic, social, psychological, health-related, and environmental determinants

should also be examined. Therefore, the present findings indicate a trend but do not directly demonstrate the causes of the increase.

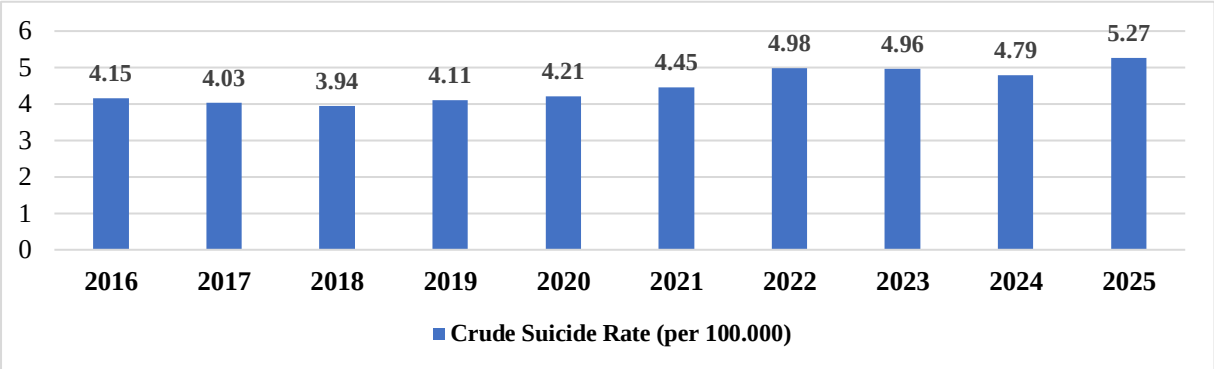


Figure 2. Crude Suicide Rate Between 2016 and 2025 (per 100,000)

Suicide Cases by Gender

Between 2016 and 2025, a total of 29,665 suicide cases were recorded among males and 8,833 among females. Accordingly, males accounted for approximately 77.1% and females for 22.9% of suicides during the ten-year period. The number of suicides among males increased from 2,426 in 2016 to 3,684 in 2025, representing a 51.9% increase. Among females, the number increased from 767 in 2016 to a period high of 1,045 in 2022 and was 915 in 2025. The numbers of suicides by gender between 2016 and 2025 are presented in Figure 3.

The higher number of suicides among males indicates a different distribution of suicide across genders. However, this finding should not be interpreted alone as evidence that males necessarily have a higher suicide risk; multiple factors underlying gender differences, including social roles, help-seeking behavior, patterns of mental health service use, economic and occupational conditions, relationship dynamics, and access to highly lethal means, should be considered together. WHO also emphasizes that suicide risk is multifactorial and that effective prevention efforts should address individual, community, and national levels (WHO, 2026).

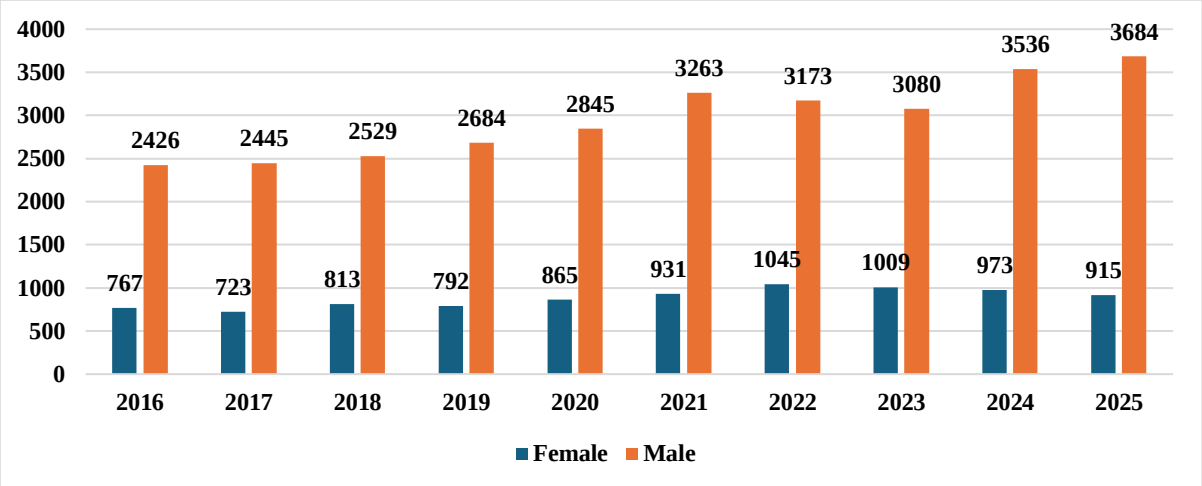


Figure 3. Number of Suicides by Gender Between 2016 and 2025

Suicides by Age Group in 2025

When suicide numbers by age group were examined in 2025, the highest number was observed in the 25–29 age group, with 594 cases (12.9%). This was followed by 537 cases (11.7%) in the 20–24 age group and 536 cases (11.7%) in the 30–34 age group. Approximately 32.7% of all suicides, or one in every three cases, occurred among people aged 15–29 years. Suicide numbers by age group in 2025 are presented in Figure 4. This finding indicates that youth and young adulthood should be considered important target groups in suicide prevention efforts. However, because the detailed age distribution was evaluated only for 2025, the present data should not be used to conclude that a particular age group

consistently constituted the highest group throughout 2016–2025. Future studies evaluating age and gender distributions together for each year would provide a more detailed time-series analysis.

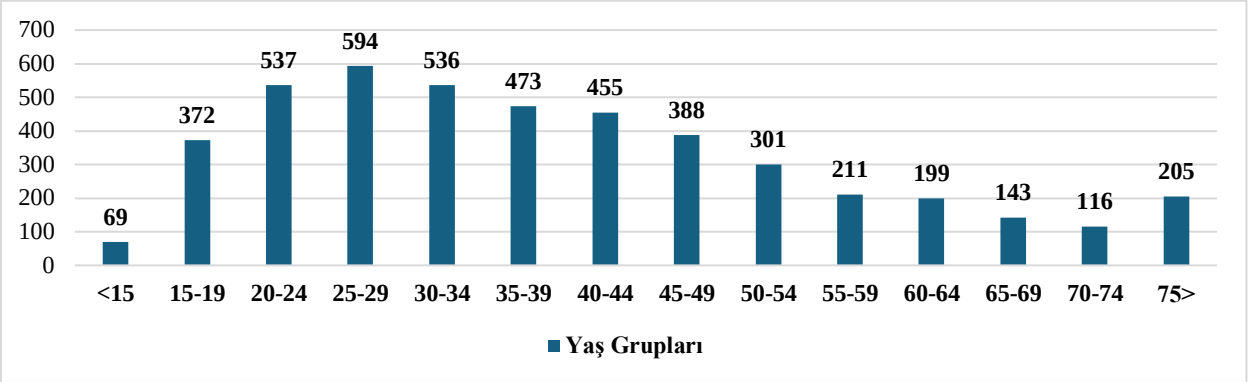


Figure 4. Number of Suicides by Age Group in 2025

Causes of Suicide in 2025

When causes of suicide were examined in 2025, the "other" category ranked first with 1,463 cases (31.8%). This was followed by illness with 1,128 cases (24.5%) and unknown causes with 1,129 cases (24.5%). "Economic problems" accounted for 452 cases (9.8%), "Family incompatibility" for 188 (4.1%), "Emotional relationship and not marrying the person wanted" for 104 (2.3%), "Business failure" for 26 (0.6%), and "educational failure" for 9 (0.2%). The numbers of suicides by cause in 2025 are presented in Figure 5. When interpreting suicide-cause data, the size of the "other" and "unknown" categories should be given particular attention. Together, these two categories accounted for 2,592 cases, approximately 56.4% of the total. Therefore, it is not possible to draw definitive conclusions about the main determinants of suicide in Türkiye based solely on explicitly classified causes. Nevertheless, the substantial numbers recorded for categories such as disease, financial hardship, and family conflict indicate that the health, economic, and social dimensions of suicide should be addressed together.

WHO reports that various life circumstances, including economic problems, relationship conflicts, chronic illness and pain, loneliness, discrimination, violence, and loss, may be associated with suicidal behavior (WHO, 2026). In this context, causes such as disease, financial hardship, and family conflict reported in official Turkish statistics indicate that suicide should not be assessed solely through psychiatric disorders. However, categories recorded as "causes" in official statistics are not equivalent to causal mechanisms at the individual level. Therefore, the current data should be interpreted within a descriptive and associative framework.

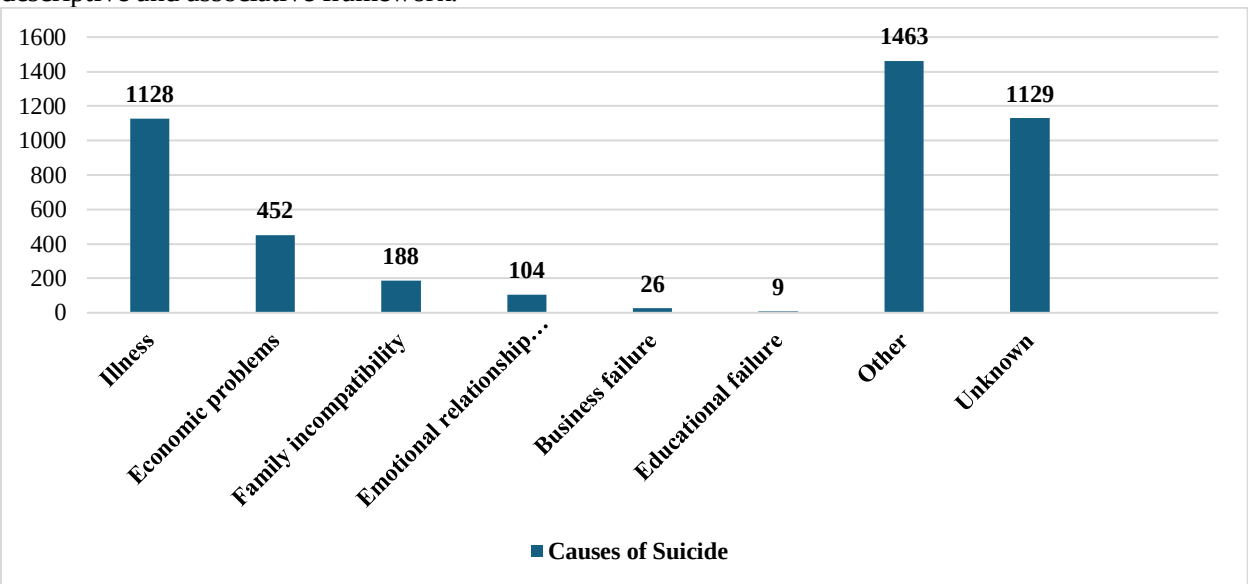


Figure 5. Number of Suicides by Cause in 2025

GENERAL DISCUSSION

The main finding of this study is the presence of an overall increasing trend in the number of suicides in Türkiye during 2016–2025. The total number increased from 3,193 in 2016 to 4,599 in 2025. During the same period, the crude suicide rate increased from 4.03 to 5.36 per 100,000, indicating that the increase cannot be explained solely by changes in population size. However, the observed trend does not by itself demonstrate that a specific social or economic factor caused the increase in suicides. Given the multifaceted nature of suicide, changes over time should be examined together with different social indicators.

The number of suicides among males was higher than among females in all years examined. This finding is generally consistent with studies reporting higher suicide mortality among males in the global literature (Turecki & Brent, 2016; World Health Organization [WHO], 2025). However, differences between genders should not be explained solely by individual characteristics. Variables such as help-seeking behavior, access to health services, gender roles, economic responsibilities, social support, and the lethality of methods used are important when evaluating gender differences.

The prominence of the 15–29 age range in the 2025 age distribution suggests that young people should be considered a visible target group in suicide prevention programs. This period involves numerous important life events, including the transition from education to working life, economic independence, family formation, social relationships, and future planning. However, because of the descriptive nature of this study, the underlying reasons for the higher numbers observed in specific age groups cannot be directly explained.

The presence of categories such as illness, economic problems, and family incompaatibility among the reported causes of suicide indicates that prevention approaches should integrate health services and social policy. WHO's "**Live Life**" approach identifies restricting access to means of suicide, responsible media reporting, strengthening life skills among young people, and early identification and support of people affected by suicidal behavior as key interventions (WHO, 2021). This approach demonstrates that suicide prevention cannot be reduced to clinical treatment alone and requires coordination across community, education, health, and other sectors.

The regular publication of official statistics is an important advantage for monitoring suicide prevention programs. However, the large "unknown" and "other" categories limit detailed interpretation of the records. Improving the quality of data on suicide causes, strengthening standardized recording procedures for determining causes of death, and, where possible, reporting variables such as age, gender, and cause together could make important contributions to future public health research.

LIMITATIONS

This study has several limitations. First, because the research was based on aggregated secondary data, individual-level risk factors, mental health status, socioeconomic characteristics, previous suicide attempts, health service use, and social support could not be evaluated. Second, because the study was descriptive, causal inferences regarding changes across years cannot be made. Third, because detailed distributions of age groups and causes of suicide were presented using 2025 data in the dataset, a detailed trend analysis of these variables across the entire 2016–2025 period could not be performed. Finally, the substantial size of the "other" and "unknown" categories in official records limits the interpretability of the distribution of causes.

CONCLUSION AND RECOMMENDATIONS

Between 2016 and 2025, the number of suicides in Türkiye generally increased; the total number of suicides rose from 3,193 to 4,599, while the crude suicide rate increased from 4.03 to 5.36 per 100,000. More than three-quarters of suicides during the ten-year period occurred among males. In 2025, high numbers were particularly observed among the 15–29 age groups, while "other," "unknown," and "disease" were the most prominent cause categories.

Based on these findings, suicide prevention efforts in Türkiye should be planned to cover different risk groups, particularly young people and males, and coordination among educational institutions, primary health care services, mental health services, emergency health services, social services, and other relevant sectors should be strengthened. Programs that enhance life skills, problem-solving, stress management, and help-seeking behaviors among young people should be expanded, and individuals at risk should be identified early and referred to appropriate services. In addition, social and health-related

areas such as economic hardship, family and relationship problems, and chronic illness should be addressed together in suicide prevention policies.

Finally, suicide data should be monitored regularly by age, gender, and cause; data quality should be improved to reduce the "unknown" and "other" categories; time-series analyses should be conducted at national and local levels; and the outcomes of prevention programs should be evaluated regularly. Given the multifaceted nature of suicide, a sustainable and evidence-based prevention approach should be implemented through multisectoral collaboration.

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PERFORMANCE EVALUATION OF A 2D LBM SOLVER FOR FLOW AROUND CYLINDERS ACROSS VARIOUS ASPECT RATIOS

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ABSTRACT
In this study, a two-dimensional Lattice Boltzmann Method (LBM) solver is employed to examine the flow past elliptical cylinders with aspect ratios (AR) from 0.50 to 2.00. The primary objective is to develop and validate a computationally efficient code for aerodynamic analyses. Simulations are performed at a constant Reynolds number of 200 to evaluate the aerodynamic forces and wake dynamics across the selected aspect ratios. To assess the reliability and accuracy of the developed solver, grid and domain independence tests and validation studies against the literature are conducted. The mean flow topology, the vortex formation length and the spatial distribution of the wake fluctuation energy are evaluated. Quantitative assessments of the baseline circular cylinder show good agreement with established benchmark data, yielding maximum relative deviations of less than 3.2% for the mean drag coefficient and the Strouhal number. Spectral analysis of the lift fluctuations yields Strouhal numbers of 0.2011, 0.2141 and 0.2097 for aspect ratios of 1.00, 0.75 and 0.50, respectively, and the value obtained for the circular cylinder agrees closely with the reference data. In terms of wake topology, the non-dimensional vortex formation length (L_f/D) of the circular cylinder is predicted as 0.86, which agrees well with the benchmark value of 0.87. Following the validation, the ratio of the RMS lift coefficient to the mean drag coefficient reaches its highest value of 0.380 at AR = 0.75. This favourable balance between fluctuating lift and mean drag appears to be associated with the intense wake fluctuation energy concentrated immediately behind the body. The mean velocity contours indicate that the AR = 0.75 configuration induces a more compact recirculation zone, reducing the vortex formation length to 0.62D. In addition, the AR = 0.75 configuration appears to accelerate wake formation, producing a compact vortex street with a higher shedding frequency.
Keywords: Computational Fluid Dynamics (CFD), Cylinder flow, Lattice Boltzmann Method, Wake dynamics, Vortex shedding.

ÖZET
Bu çalışmada, en-boy oranları 0,50 ile 2,00 arasında değişen eliptik silindirlerin etrafındaki akış incelenmek üzere iki boyutlu Lattice Boltzmann Yöntemi (LBM) kullanılmıştır. Çalışmanın temel amacı, aerodinamik analizler için hesaplama açısından verimli bir sayısal kod geliştirmek ve doğrulamaktır. Seçilen en-boy oranları için aerodinamik kuvvetleri ve iz bölgesi dinamiklerini değerlendirmek amacıyla simülasyonlar sabit Reynolds sayısı Re = 200 koşulunda gerçekleştirilmiştir. Geliştirilen çözücünün güvenilirliğini ve doğruluğunu değerlendirmek amacıyla ağ ve çözüm alanı bağımsızlık testleri ile literatürdeki referans çalışmalarla doğrulama çalışmaları yürütülmüştür. Ortalama akış topolojisi, girdap oluşum uzunluğu ve iz bölgesi dalgalanma enerjisinin uzaysal dağılımı değerlendirilmiştir. Referans dairesel silindir için gerçekleştirilen nicel karşılaştırmalar, literatürdeki kıyaslama verileriyle iyi bir uyum göstermiştir. Doğrulama sonucunda ortalama sürükleme katsayısı ve Strouhal sayısı açısından maksimum bağıl sapmaların %3,2'nin altında olduğu belirlenmiştir. Kaldırma kuvveti dalgalanmalarının spektral analizi sonucunda AR = 1,00, 0,75 ve 0,50 için Strouhal sayıları sırasıyla 0,2011, 0,2141 ve 0,2097 olarak elde edilmiş, dairesel silindir için elde edilen değerin referans verilerle uyumlu olduğu görülmüştür. İz bölgesi topolojisi açısından, dairesel silindir için boyutsuz girdap oluşum uzunluğu (L_f/D) 0,86 olarak tahmin edilmiş ve bu değer 0,87 olan referans değerle iyi bir uyum göstermiştir. Doğrulamanın ardından yapılan incelemede, RMS kaldırma katsayısının ortalama sürükleme katsayısına oranı en yüksek değeri olan 0,380'e AR = 0,75 durumunda ulaşmıştır. Kaldırma

kuvveti ile ortalama sürükleme arasındaki bu ilişkinin, cismin hemen arkasında yoğunlaşan yüksek enerjili iz bölgesi ile ilişkili olduğu görülmüştür. Ortalama hız konturları, AR = 0,75 konfigürasyonunun daha kompakt yeniden dolaşım bölgesi oluşturduğunu ve girdap oluşum uzunluğunun 0,62D seviyesine düştüğünü göstermiştir. Ayrıca, AR = 0,75 durumunda iz bölgesinin oluşumunun hızlandığı ve daha yüksek girdap kopma frekansına sahip kompakt bir girdap bölgesinin meydana geldiği gözlemlenmiştir.
Anahtar Kelimeler: Hesaplamalı Akışkanlar Dinamiği (HAD), Silindir etrafındaki akış, Lattice Boltzmann Yöntemi, İz bölgesi dinamikleri, Girdap kopması.

INTRODUCTION

Flow past bluff bodies remains one of the most widely studied problems in fluid mechanics, since the periodic shedding of vortices from such bodies governs the unsteady loads acting on heat exchanger tubes, offshore risers, bridge decks, chimneys and a wide range of aerodynamic components. For a circular cylinder, the wake becomes unsteady beyond a critical Reynolds number of approximately 47 and develops the well-known von Kármán vortex street, whose frequency and strength determine the fluctuating lift and drag experienced by the structure (Williamson, 1989). Although three-dimensional wake instabilities are reported to appear at Reynolds numbers close to 190 (Henderson, 1997), two-dimensional simulations at Re = 200 are still commonly used as a benchmark configuration, because the integral quantities of interest, such as the mean drag coefficient, the root-mean-square (RMS) lift coefficient and the Strouhal number, are well documented and remain reasonably predicted in this regime (Henderson, 1997; Rajani et al., 2009).

Departing from the circular cross-section introduces an additional geometric degree of freedom that can change the separation behaviour, the size of the recirculation region and the resulting fluid forces considerably. Elliptical cylinders offer a convenient way to explore this effect, since a single parameter, the aspect ratio, allows a continuous transition from a bluff, plate-like body to a streamlined one. Thompson et al. (2014) showed that the wake transitions of elliptical cylinders change markedly as the cross-section is varied from a circular cylinder towards a normal flat plate. Shi et al. (2020) identified distinct wake patterns for elliptical cylinders at Re = 150 depending on the aspect ratio and angle of attack, while Pradhan et al. (2022) reported that the drag coefficient, the lift contributions and the Strouhal number respond non-uniformly to changes in aspect ratio at low Reynolds numbers. More recently, Celik and Kiziloglu (2026) suggested that the elliptical bluffness of a cylinder can be exploited to amplify transverse force fluctuations and thereby enhance vortex-induced vibration excitation, which appears relevant for flow-induced energy harvesting applications. These findings indicate that the aspect ratio could serve as an effective passive parameter for tailoring the balance between drag and lift fluctuations.

Most of the studies cited above rely on conventional Navier-Stokes solvers based on finite-volume or spectral-element discretisations. The Lattice Boltzmann Method (LBM) has emerged as an alternative, in which the macroscopic flow is recovered from the evolution of particle distribution functions on a regular lattice through a local collision step and a simple streaming step (Krüger et al., 2017). This algorithmic structure makes the method suitable for parallel and GPU architectures and allows complex or moving boundaries to be treated on Cartesian grids without body-fitted meshing. Mature general-purpose frameworks such as Palabos (Lätt et al., 2021) and OpenLB (Krause et al., 2021) have demonstrated the scalability of the approach, and recent work has examined how numerical precision affects the accuracy and performance of LBM implementations (Lehmann et al., 2022). The method has also been applied to bluff-body problems, including the onset of vortex shedding from rectangular cylinders of different aspect ratios (Tahir et al., 2023) and the flow around multiple square-like cylinders with rounded corners using the immersed boundary-lattice Boltzmann method (Wang et al., 2023), whose momentum exchange formulation was improved by Hu et al. (2014).

Nevertheless, general-purpose LBM frameworks can be relatively large and demanding to adapt, whereas a lightweight in-house solver may be more practical for rapid parametric studies, such as the aspect-ratio sweep considered here. For such solvers to be used with confidence, their ability to reproduce benchmark force coefficients and wake topology metrics should be demonstrated. However, the performance of compact two-dimensional LBM codes has not been examined in this manner for elliptical cylinders of different aspect ratios.

In this context, the present study develops a two-dimensional LBM solver and evaluates its performance for the flow past cylinders with aspect ratios between 0.50 and 2.00 at Re = 200. The solver is first

verified through grid and domain independence tests and validated against established benchmark data for the circular cylinder. It is then used to quantify the effect of the aspect ratio on the mean drag coefficient, the RMS lift coefficient, the Strouhal number, the ratio of lift fluctuation to drag, the vortex formation length and the spatial distribution of the wake fluctuation energy. The remainder of the paper is organised as follows, the numerical method and computational set-up are described in the next section, the results are presented and discussed thereafter, and the main conclusions are summarised in the final section.

MATERIALS AND METHODS

Lattice Boltzmann formulation

The flow is modelled with a two-dimensional in-house solver based on the Lattice Boltzmann equation with the single-relaxation-time Bhatnagar-Gross-Krook (BGK) collision operator and the standard D2Q9 velocity set (Krüger et al., 2017). The evolution of the particle distribution functions f_i is expressed as

$$f_i(\mathbf{x} + \mathbf{c}_i \Delta t,\ t + \Delta t) - f_i(\mathbf{x}, t) = -\frac{1}{\tau}\left[f_i(\mathbf{x}, t) - f_i^{\mathrm{eq}}(\mathbf{x}, t)\right] \qquad (1)$$

where $\mathbf{c}_i$ are the discrete lattice velocities, Δt is the time step and τ is the dimensionless relaxation time. The equilibrium distribution is given by the second-order expansion of the Maxwell-Boltzmann distribution,

$$f_i^{\mathrm{eq}} = w_i \rho \left[1 + \frac{\mathbf{c}_i \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_i \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u} \cdot \mathbf{u}}{2c_s^2}\right] \qquad (2)$$

in which the weighting factors are $w_0 = 4/9$ for the rest particle, $w_{1\ldots4} = 1/9$ for the axial directions and $w_{5\ldots8} = 1/36$ for the diagonal directions, and $c_s = 1/\sqrt{3}$ is the lattice speed of sound. The macroscopic density and momentum are obtained from the moments of the distribution functions,

$$\rho = \sum_{i=0}^{8} f_i\,, \qquad \rho\mathbf{u} = \sum_{i=0}^{8} f_i\ \mathbf{c}_i \qquad (3)$$

and the kinematic viscosity is related to the relaxation time through

$$\nu = c_s^2 \left(\tau - \frac{1}{2}\right) \Delta t \qquad (4)$$

Through the Chapman-Enskog expansion, this scheme recovers the incompressible Navier-Stokes equations in the low Mach number limit (Krüger et al., 2017). Each time step consists of a local collision at the fluid nodes followed by a pull-type streaming step to the neighbouring nodes. The solver is written in Python, and the collision and streaming kernels are compiled just-in-time with Numba and parallelised over the lattice rows, while a vectorised NumPy implementation of the same operations is retained as a fallback.

Geometry, computational domain and boundary conditions

The investigated bodies are elliptical cylinders whose transverse (cross-flow) dimension D is kept constant, while the streamwise dimension is varied. The aspect ratio is defined as the ratio of the streamwise length to the cross-flow width, so that the transverse and streamwise semi-axes are $b = D/2$ and $a = AR \cdot D/2$, respectively. A lattice node is flagged as solid when its polar coordinates (r, θ) relative to the body centre satisfy

$$r \le R(\theta) = \frac{ab}{\sqrt{(b\cos\theta)^2 + (a\sin\theta)^2}} \quad (5)$$

Accordingly, $AR < 1$ corresponds to blunt bodies compressed in the streamwise direction, $AR = 1$ to the circular cylinder and $AR > 1$ to slender, streamlined bodies. Five cases are considered, namely $AR =$ 0.50, 0.75, 1.00, 1.33 and 2.00, which are listed as Case 1 to Case 5 in Table 4. Since D is the frontal width for every case, the blockage ratio remains identical, and Re and all force coefficients share the same reference length, which allows a direct comparison between the configurations.

The rectangular computational domain extends $32D$ in the streamwise direction and $16D$ in the transverse direction, which corresponds to a lattice of 1600 × 800 nodes for the selected resolution. The body centre is placed $8D$ downstream of the inlet and on the domain centreline, providing a wake region of $24D$ and a blockage ratio of $D/H = 6.25\%$. At the inlet, the populations are set to the equilibrium distribution of Eq. (2) with $\rho = 1$ and a uniform velocity U_∞. To limit the initial pressure waves, the inlet velocity is increased from zero following a cosine ramp over the first 2000 time steps, and during this ramp a small transverse velocity component equal to 5% of the instantaneous inlet velocity is superimposed to break the flow symmetry and trigger vortex shedding. At the outlet, a pressure

boundary condition based on the anti-bounce-back scheme is imposed, in which the unknown incoming populations are reconstructed as

$$f_{\bar{\imath}}(\mathbf{x}_b) = -f_i(\mathbf{x}_b) + 2w_i\rho_0\left[1 + \frac{(\mathbf{c}_i\cdot\mathbf{u}_b)^2}{2c_s^4} - \frac{\mathbf{u}_b\cdot\mathbf{u}_b}{2c_s^2}\right] \qquad (6)$$

where $\bar{\imath}$ denotes the direction opposite to i, $\rho_0 = 1$ is the prescribed outlet density and $\mathbf{u}_b$ is the velocity at the adjacent interior node. Prescribing the outlet pressure in this way allows the flow rate to adjust freely, so that global mass conservation is maintained without artificial density corrections. Free-slip conditions are applied on the lateral boundaries through the specular reflection of the populations. The no-slip condition on the body is enforced with the full-way bounce-back scheme, in which no collision is performed at the solid nodes and the populations streaming into them are reflected in the opposite direction. The hydrodynamic forces are evaluated at every time step with the momentum exchange method, by summing the momentum carried by the populations reflected at the solid nodes.

Flow parameters and post-processing

The Reynolds number based on the cross-flow width, $Re = U_\infty D/\nu$, is fixed at 200 for all cases. With $D = 50$ lattice units, $U_\infty = 0.08$ and $\nu = 0.02$ in lattice units, Eq. (4) gives $\tau = 0.56$, and the corresponding Mach number, $Ma = U_\infty/c_s \approx 0.14$, remains well below the limit commonly accepted for weakly compressible LBM simulations. The flow is initialised at rest with $\rho = 1$. The drag and lift coefficients and the Strouhal number are defined as

$$C_d = \frac{F_x}{1/2\rho U_\infty^2 D}, \qquad C_l = \frac{F_y}{1/2\rho U_\infty^2 D}, \qquad St = \frac{fD}{U_\infty} \qquad (7)$$

where F_x and F_y are the streamwise and transverse force components per unit span and f is the dominant vortex shedding frequency. Rather than prescribing an arbitrary number of iterations, the simulation length is derived from the physical time scales of the problem. The first 50,000 time steps, corresponding to 2.5 domain flow-through times (N_x/U_∞), are discarded as the initial transient. Statistics are then collected over a further 93,750 time steps, which corresponds to approximately 30 vortex shedding periods, giving a total of 143,750 time steps per case. The mean drag coefficient $\overline{C_d}$ and the RMS lift coefficient $C_{l,\mathrm{rms}}$ are computed over this window, and f is obtained from the Hann-windowed fast Fourier transform of the lift signal, with parabolic interpolation around the spectral peak to refine the frequency estimate. To confirm that the statistics are not affected by a slowly developing drift, the window is divided into five equal segments, and the ratio of $C_{l,\mathrm{rms}}$ in the last segment to that in the second segment is required to lie between 0.85 and 1.18. The ratio $C_{l,\mathrm{rms}}/\overline{C_d}$ is adopted as a measure of the transverse force fluctuation obtained per unit mean drag, which is relevant for flow-induced vibration and energy harvesting applications.

The wake topology is characterised through the velocity field averaged over the same statistics window. The vortex formation length L_f is measured along the wake centreline from the rear stagnation point of the body ($x = x_c + a$) to the first location where the mean streamwise velocity becomes non-negative, i.e. the downstream end of the mean recirculation region. In addition, up to 350 velocity snapshots, equally spaced over the statistics window (about 11 snapshots per shedding cycle), are stored in a wake region extending from $1.5D$ upstream to $15D$ downstream of the body centre and $\pm 4D$ in the transverse direction. From these snapshots, the wake fluctuation energy is computed as $WFE = 1/2\left(\overline{u'^2} + \overline{v'^2}\right)/U_\infty^2$, where u' and v' are the fluctuating velocity components, and its spatial distribution is used to locate the regions of intense unsteadiness in the near wake. Instantaneous vorticity is presented in the normalised form $\omega_z D/U_\infty$.

Grid and domain independence

The sensitivity of the solution to the lattice resolution was examined for the circular cylinder using 25, 50 and 100 lattice nodes per diameter, with the finest resolution taken as the reference (Table 1). Increasing the resolution from 50 to 100 nodes changes $\overline{C_d}$, $C_{l,\mathrm{rms}}$ and St by 1.2%, 3.3% and 0.1%, respectively, whereas the coarsest lattice yields deviations of up to 8.9%. Accordingly, a resolution of 50 nodes per diameter was selected as a reasonable compromise between accuracy and computational cost. The influence of the domain size was then assessed with domains of $20D \times 10D$, $32D \times 16D$ and $48D \times 24D$ (Table 2). Relative to the largest domain, the $32D \times 16D$ domain differs by 2.0%, 3.5% and 1.0% in $\overline{C_d}$, $C_{l,\mathrm{rms}}$ and St, respectively, while the smallest domain produces deviations exceeding

11% in $C_{l,\mathrm{rms}}$, which is likely attributable to stronger confinement effects. The $32D \times 16D$ domain was therefore adopted for all subsequent simulations. The validation of the selected configuration against benchmark data for the circular cylinder (Henderson, 1997; Williamson, 1989; Rajani et al., 2009; Hu et al., 2014; Celik and Kiziloglu, 2026) is presented in the following section. In Tables 1 to 3, the relative deviation is defined as $\varepsilon = |\varphi - \varphi_{\mathrm{ref}}|/\varphi_{\mathrm{ref}} \times 100$, where φ_{ref} is the value obtained on the finest lattice (Table 1), on the largest domain (Table 2), or reported in the literature (Table 3).

Table 1. Grid independence test.

Nodes per D	□□ [−]	□□□□ [−]	□□ [−]	□□ □ [%]	□□□□ □ [%]	□□ □ [%]
25	1.46219	0.54697	0.19884	5.1	8.9	1.0
50	1.37522	0.48599	0.20109	1.2	3.3	0.1
100	1.39124	0.50235	0.20087	-	-	-

Table 2. Domain independence test.

Domain Size	□□ [−]	□□□□ [−]	□□ [−]	□□ □ [%]	□□□□ □ [%]	□□ □ [%]
□□□ × □□□	1.43477	0.52277	0.20713	6.4	11.3	4.1
□□□ × □□□	1.37522	0.48599	0.20109	2.0	3.5	1.0
□□□ × □□□	1.34888	0.46963	0.19904	-	-	-

FINDINGS AND DISCUSSION

The independence studies were conducted, and then the developed solver was validated against benchmark data reported for the flow past a circular cylinder at Re = 200. The mean drag coefficient, the RMS lift coefficient, and the Strouhal number obtained in the present study are compared with the results of Henderson (1997), Williamson (1989), Hu et al. (2014), Rajani et al. (2009), and Celik and Kiziloglu (2026), as shown in Table 3.

The present solver predicts a mean drag coefficient of 1.3752, which deviates from the reference values by between 1.35% and 3.17%. Similarly, the Strouhal number of 0.2011 is in close agreement with the literature, and the corresponding deviations range from 2.08% to 3.12%. As the maximum relative deviation obtained for these two parameters is below 3.2%, the present solver is considered sufficiently accurate to capture both the mean drag and the shedding frequency. Furthermore, the RMS lift coefficient of the present study is 0.4860, which falls between the values of Rajani et al. (2009) and Hu et al. (2014), and is only 1.99% higher than that of Celik and Kiziloglu (2026). In addition, the mean wake topology was compared with the reference data of Celik and Kiziloglu (2026), as shown in Figure 1. The mean streamwise velocity field and the extent of the recirculation region are reproduced with good fidelity by the present numerical approach. The non-dimensional vortex formation length (L_f/D) is predicted as 0.86, which is approximately 1% lower than the reference value of 0.87. The results indicate that the present numerical solver is able to resolve the near-wake structure and to predict the aerodynamic forces.

Table 3. Comparison of the present results with previous studies.

	□□ [−]	□□□□ [−]	□□ [−]	□□ □ [%]	□□□□ □ [%]	□□ □ [%]
Present Study	1.37522	0.48599	0.20109	-	-	-
Henderson (1997)	1.340	-	0.197	2.63	-	2.08
Williamson (1989)	-	-	0.197	-	-	2.08
Hu et al. (2014)	1.394	0.499	0.195	1.35	2.61	3.12
Rajani et al. (2009)	1.337	0.4244	0.1957	2.86	14.51	2.75
Celik and Kiziloglu (2026)	1.333	0.4765	0.1953	3.17	1.99	2.96

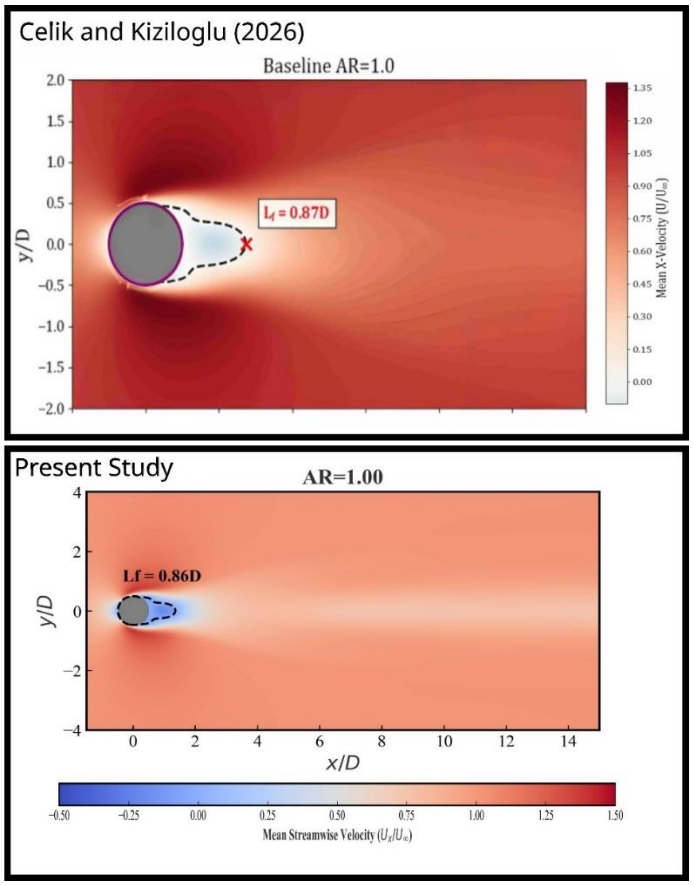


Figure 1. Mean streamwise velocity contours and vortex formation length for AR = 1.00, Celik and Kiziloglu (2026) (top) and the present study (bottom).

After completing the validation process, the effects of the aspect ratio on the aerodynamic forces and wake characteristics were systematically investigated for five configurations, with aspect ratios ranging from 0.50 to 2.00. The resulting aerodynamic force coefficients are summarised in Table 4 and illustrated in Figures 2 and 3.

Table 4. Computational results of the aerodynamic parameters for the different aspect ratios.

	□□	$\overline{□_□}$ [−]	□□□□ [−]	□□ [−]
Case 1	0.50	2.1015	0.6863	0.2097
Case 2	0.75	1.7045	0.6483	0.2141
Case 3	1.00	1.3752	0.4860	0.2011
Case 4	1.33	1.1431	0.3060	0.1935
Case 5	2.00	0.9543	0.1536	0.1959

The mean drag coefficient decreases monotonically with increasing aspect ratio, as shown in Figure 2. The maximum value of 2.1015 is obtained for an aspect ratio of 0.50, whereas the minimum mean drag coefficient of 0.9543 corresponds to an aspect ratio of 2.00. This trend is qualitatively consistent with those reported for elliptical cylinders at low Reynolds numbers (Thompson et al., 2014; Shi et al., 2020), although a direct quantitative comparison is not possible owing to differences in Reynolds number and blockage. The RMS lift coefficient in Figure 3 shows a similar trend, decreasing from 0.6863 at AR = 0.50 to 0.1536 at AR = 2.00. Higher aspect ratios lead to considerably lower force fluctuations, indicating a reduced vortex shedding intensity. The Strouhal number, however, follows a different trend from the mean drag and RMS lift coefficients. It reaches a maximum value of 0.2141 at AR = 0.75 and decreases to 0.1935 at AR = 1.33. For AR ≥ 1.33, the Strouhal number remains nearly unchanged, and the difference between the AR = 1.33 and AR = 2.00 cases is smaller than the raw spectral resolution ($\Delta St \approx 0.007$); this difference should therefore be interpreted with caution.

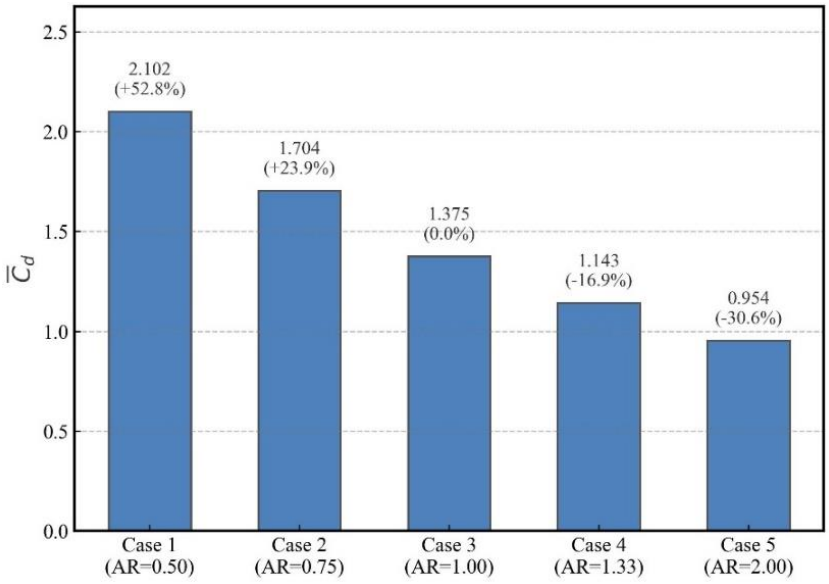


Figure 2. Mean drag coefficient across different aspect ratios.

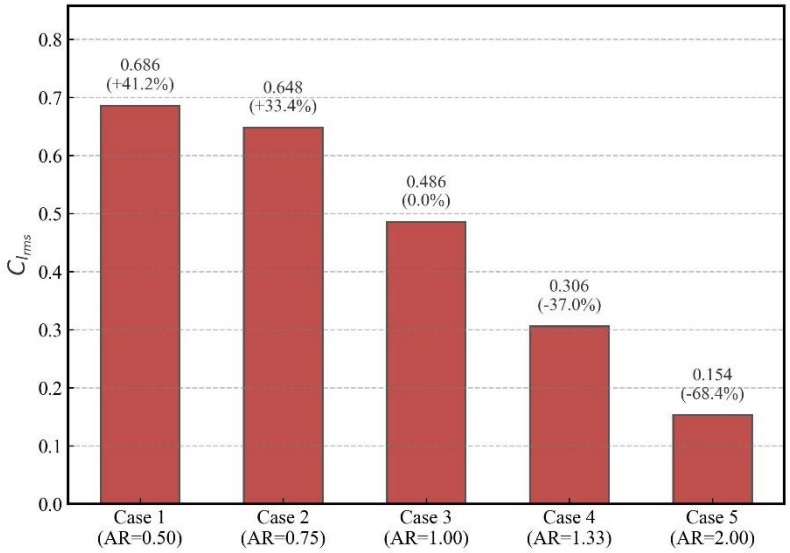


Figure 3. RMS lift coefficient across different aspect ratios.

The ratio of the RMS lift coefficient to the mean drag coefficient is presented in Figure 4. This ratio reaches its maximum value of 0.380 at AR = 0.75. For the more streamlined bodies with AR > 1, the ratio decreases rapidly, reaching 0.161 at AR = 2.00. The body with an aspect ratio of 0.50 generates the largest absolute lift fluctuation; however, it also experiences the highest mean drag among all cases. Accordingly, the AR = 0.75 case combines a strong fluctuating lift with a lower mean drag than the AR = 0.50 case.

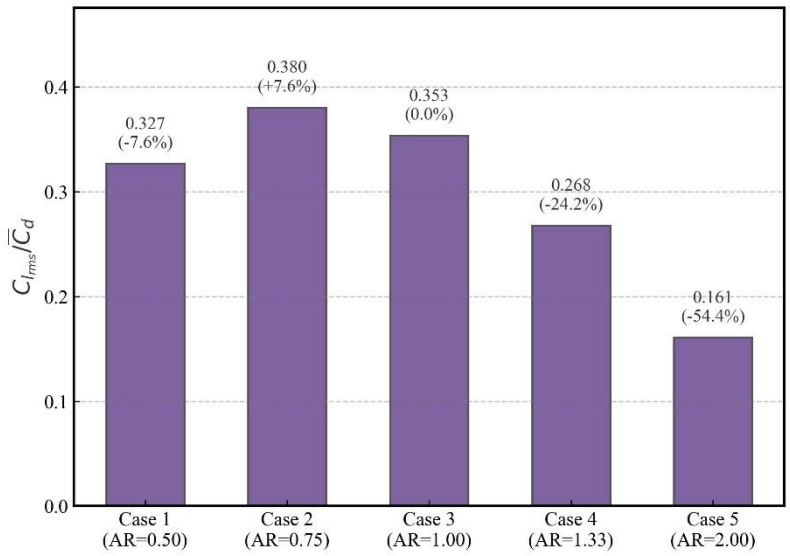


Figure 4. RMS lift coefficient to the mean drag coefficient ratio across different aspect ratios.

The spatial distribution of the wake fluctuation energy (WFE) is presented in Figure 5 for the configurations with aspect ratios of 1.00 and 0.75. For the baseline circular cylinder, the fluctuation energy peaks at about 0.24 in the near wake. The AR = 0.75 configuration shows a similar pattern, but the energy is concentrated closer to the body and its peak value is about 0.35, which is approximately 45% higher than that of the baseline case. In addition, the fluctuation energy remains higher than that of the baseline case along the wake. The more intense fluctuation energy of the AR = 0.75 body suggests a stronger and more rapid roll-up of the separated shear layers, in line with its higher RMS lift coefficient (Table 4).

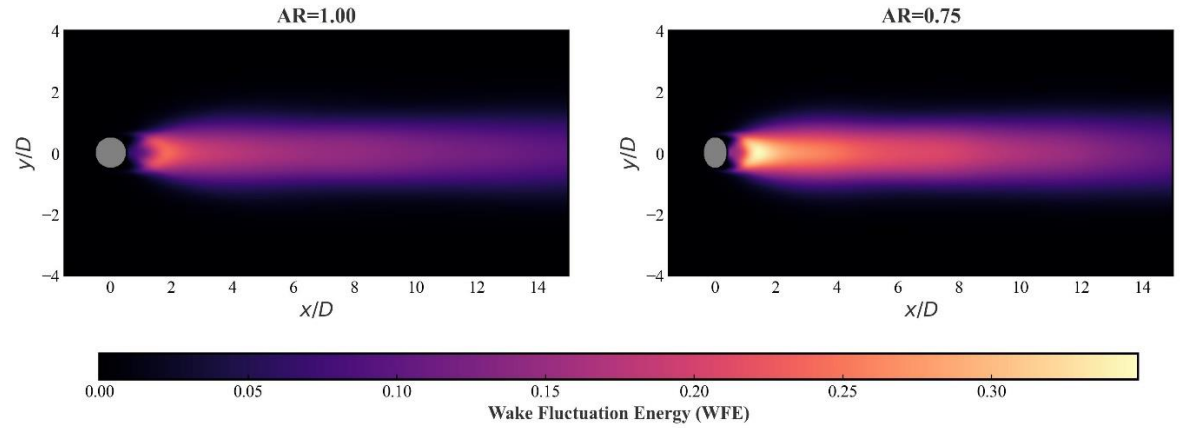


Figure 5. Spatial distribution of wake fluctuation energy for the cylinders with aspect ratios of 1.00 and 0.75.

The mean streamwise velocity contours and the corresponding vortex formation lengths are compared in Figure 6. The vortex formation length, L_f, is the length of the mean recirculation region behind the body. It is measured along the wake centreline from the rear of the body to the point where the mean streamwise velocity becomes zero and is shown by the dashed contour in Figure 6. For the baseline circular cylinder, the recirculation region extends to L_f = 0.86D. On the other hand, the recirculation region is shorter for the aspect ratio of 0.75, at 0.62D. As a result, the wake begins to recover towards the free-stream value closer to the body. The shorter formation length obtained for AR = 0.75 is consistent with both the amplified wake fluctuation energy shown in Figure 5 and the higher RMS lift coefficient reported in Table 4.

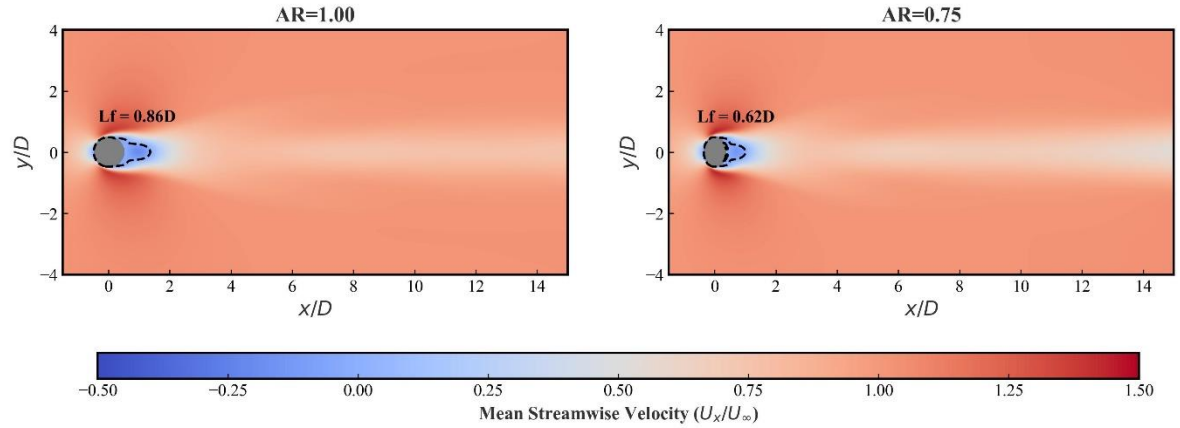


Figure 6. Mean streamwise velocity contours and vortex formation lengths for the cylinders with aspect ratios of 1.00 and 0.75.

The instantaneous normalised spanwise vorticity fields for the AR = 0.75 and AR = 1.00 configurations are compared in Figure 7. A fully developed von Kármán vortex street is observed for both cases. However, behind the AR = 0.75 cylinder, the shear layers roll up closer to the body, which leads to a denser vortex street. This behaviour corresponds to a higher Strouhal number of 0.214 for an aspect ratio of 0.75. These observations are supported by the wake fluctuation energy distribution shown in Figure 5 and by the mean flow topology presented in Figure 6.

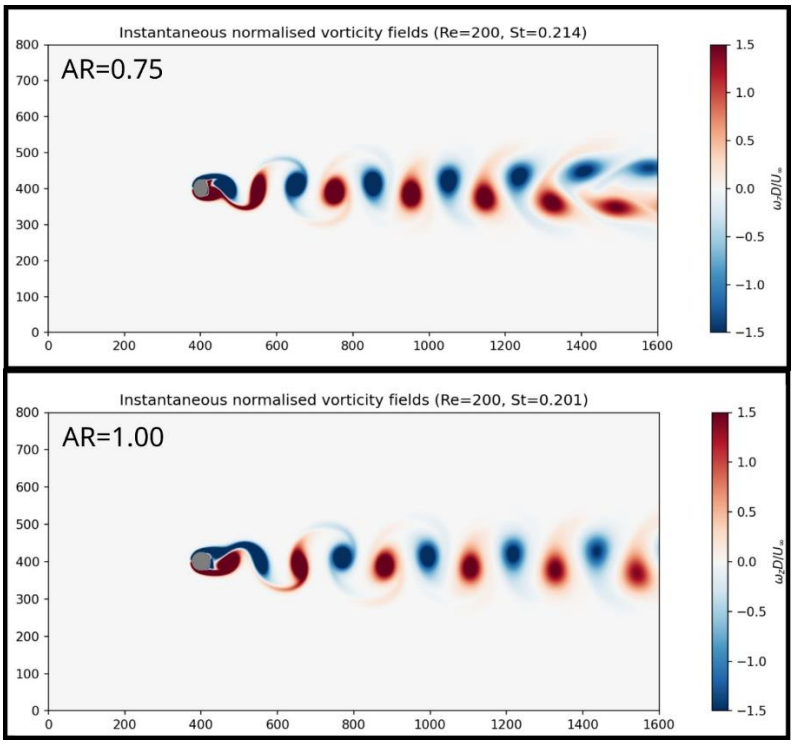


Figure 7. Instantaneous normalised spanwise vorticity fields for the cylinders with aspect ratios of 0.75 (top) and 1.00 (bottom) at Re = 200.

CONCLUSION AND RECOMMENDATIONS

A two-dimensional Lattice Boltzmann solver was developed and applied to the flow past cylinders with aspect ratios ranging from 0.50 to 2.00 at a Reynolds number of 200. The solver was verified through grid and domain independence studies and validated against benchmark data, with maximum deviations below 3.2% for the mean drag coefficient and the Strouhal number, and a predicted vortex formation length of 0.86D against the reference value of 0.87D. The mean drag and RMS lift coefficients decreased monotonically with increasing aspect ratio. The aspect ratio also affected the vortex shedding frequency, as the Strouhal number reached its maximum value of 0.2141 at an aspect ratio of 0.75, while it remained nearly unchanged (0.1935 and 0.1959) for the more streamlined bodies with AR ≥ 1.33.

The ratio of the RMS lift coefficient to the mean drag coefficient reached its highest value of 0.380 at an aspect ratio of 0.75. The wake analyses showed that this configuration shortened the vortex formation length from 0.86D to 0.62D. The shorter formation length was consistent with a shear-layer roll-up closer to the body and a more energetic vortex street.

These results are subject to some limitations. The simulations are two-dimensional, whereas three-dimensional wake instabilities are expected near Re = 200. The full-way bounce-back scheme represents the curved surface in a staircase manner, which is most restrictive for AR = 0.50, whose streamwise thickness spans only 25 lattice nodes. Future work will address interpolated or immersed boundary treatments, a wider Reynolds number range, and the coupling of the solver with a structural model to quantify the actual vortex-induced vibration response.

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A NUMERICAL ASSESSMENT OF AN INCLINED FLAT PLATE WITH A SEMICIRCULAR CYLINDER FOR FLOW-INDUCED ENERGY HARVESTING

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ABSTRACT
This study presents a numerical investigation of unsteady flow past a 30º inclined flat plate at a Reynolds number of 150,000. The simulations are carried out using the OpenFOAM 2406 computational fluid dynamics framework. The reliability of the numerical setup is established through systematic mesh and time-step independence tests. The aerodynamic behaviour of the baseline flat plate is validated against experimental and numerical data from the literature. Following the validation phase, a geometric modification is introduced by attaching a semicircular cylinder with a non-dimensional diameter (d^*) of 0.14 to the lower surface of the plate. This modification is evaluated under three positional configurations. Results indicate that the time-averaged drag and lift coefficients remain virtually constant across all configurations, varying by less than 2%. On the other hand, the position of the passive element strongly governs the wake topology, the transition behaviour, and the aerodynamic force fluctuations. In the leading-edge configuration (V1), the modification has a negligible effect on the forces and the wake, and the flow remains essentially identical to the baseline plate. In the mid-chord configuration (V2), the element confines the recirculation region and stabilises the near wake. This leads to a rapid transition to the periodic regime and a 10.5% reduction in the root-mean-square lift fluctuations ($C_{L_{rms}}$). Thus, the V2 configuration is effective in suppressing vortex-induced vibrations (VIV). The trailing-edge configuration (V3) enhances the roll-up of the shear layer and produces larger, more energetic vortices. As a result, the root-mean-square lift fluctuations increase by 8.9% and the Strouhal number decreases to 0.335, which indicates a potential for flow-induced energy harvesting.
Keywords: Computational Fluid Dynamics (CFD), Energy Harvesting, Flow-Induced Vibration (FIV), Inclined Flat Plate, OpenFOAM, Unsteady Aerodynamics.

ÖZET
Bu çalışmada, Reynolds sayısının 150.000 olduğu koşulda 30° eğimli bir düz plaka etrafındaki zamana bağlı akış sayısal olarak incelenmiştir. Simülasyonlar, OpenFOAM 2406 hesaplamalı akışkanlar dinamiği yazılımı ile gerçekleştirilmiştir. Sayısal modelin güvenilirliği, sistematik ağ ve zaman adımı bağımsızlık testleri ile ortaya konmuştur. Referans düz plakanın aerodinamik davranışı, literatürdeki deneysel ve sayısal verilerle doğrulanmıştır. Doğrulama aşamasının ardından, plakanın alt yüzeyine boyutsuz çapı (d*) 0,14 olan yarım daire kesitli bir silindir eklenerek geometrik bir modifikasyon uygulanmıştır. Bu modifikasyon üç farklı konumda değerlendirilmiştir. Sonuçlar, zaman-ortalama sürükleme ve kaldırma katsayılarının tüm konfigürasyonlarda %2'den daha az değiştiğini göstermiştir. Buna karşın, pasif elemanın konumu art-iz topolojisini, rejim geçiş davranışını ve aerodinamik kuvvet dalgalanmalarını önemli ölçüde etkilemiştir. Hücum kenarı konfigürasyonunda (V1), modifikasyonun kuvvetler ve art-iz üzerindeki etkisi ihmal edilebilir düzeydedir ve akış, referans plakayla neredeyse özdeş kalmıştır. Orta bölge konfigürasyonunda (V2), resirkülasyon bölgesi yarım silindir tarafından sınırlandırılmış ve yakın art-izi kararlı hale gelmiştir. Bu durum, periyodik rejime hızlı bir geçişe ve kaldırma kuvveti dalgalanmasında %10,5 civarında bir azalmaya yol açmıştır. Dolayısıyla V2 konfigürasyonu, girdap kaynaklı titreşimlerin (VIV) bastırılmasında etkili bir rol oynamıştır. Firar kenarı konfigürasyonu (V3) ise kesme tabakasının yuvarlanmasını güçlendirmiş ve daha enerjik girdapların üretilmesine sebep olmuştur. Sonuç olarak, kaldırma kuvveti dalgalanması %8,9 oranında artmış ve Strouhal sayısı 0,335'e düşmüştür. Bu durum V3 modifikasyonunun akış kaynaklı enerji hasadı için bir potansiyele sahip olduğunu göstermiştir.
Anahtar Kelimeler: Hesaplamalı Akışkanlar Dinamiği (HAD), Enerji Hasadı, Akış Kaynaklı Titreşim, Eğik Düz Plaka, OpenFOAM, Zamana Bağlı Aerodinamik.

INTRODUCTION

The phenomenon of flow over bluff bodies involves complex vortex dynamics and wake structures. Vortex-induced vibrations (VIV) are triggered by flow separation from the sharp edges of bluff bodies and the von Kármán vortex street (Williamson, 1996). These vibrations are considered critical engineering problems that lead to fatigue loads on several systems such as bridges, heat exchangers, underwater pipes, and high buildings (Bearman, 1984). To mitigate these loads, VIV are commonly suppressed using passive bluff-body modifications such as splitter plates and control rods (Zhu and Yao, 2015; Law and Jaiman, 2017).

In recent years, however, vortex-induced vibrations have been recognised as a sustainable energy solution that can generate electricity for low-power sensors. The mechanical displacement caused by fluid flow is converted into useful electrical energy by employing piezoelectric patches or electromagnetic systems (Mehmood et al., 2013; Alhadidi and Daqaq, 2016). In this regard, vortex-induced vibrations are enhanced to maximise energy harvesting potential using bluff-body designs such as cross-sectional modifications and leeward surface protrusions (Sun et al., 2019; Xing et al., 2024). For instance, Lei and Sun (2023a) added a splitter plate with a tuned afterbody length to a semicircular wall. This modification caused the wake to evolve from VIV to galloping. In a later study, Lei and Sun (2023b) placed upstream bluff bodies ahead of the wall to achieve the same transition.

The inclined flat plate is another widely studied bluff-body geometry. It is a fundamental case for investigating fully separated flows (Fage and Johansen, 1927), since separation is fixed at the sharp edges of the plate, making the wake largely insensitive to the Reynolds number (Re) (Chen and Fang, 1996). First, Fage and Johansen (1927) experimentally investigated the flow over an inclined flat plate and reported the pressure distribution and wake characteristics at various inclination angles. They concluded that the vortex shedding frequency increased as the inclination angle decreased. In addition, vortex production was identical at both sharp edges. Chen and Fang (1996) evaluated the Strouhal number of a flat plate with bevelled sharp edges. The experiments were performed at angles of attack (α) from 0° to 90° and Reynolds numbers from 3.5×10^3 to 3.2×10^4. Their results showed that the Reynolds number has no significant effect on the Strouhal number in the fully separated regime (α = 10°–90°), while its influence becomes significant at low incidence due to flow reattachment. Shademan and Naghib-Lahouti (2020) investigated an inclined flat plate using large-eddy simulation (LES) to provide a detailed description of the wake structure. The inclined flat plate is further investigated for flow-induced energy harvesting, as the sharp edges produce a stable and predictable wake. The plate frequently acts as the main oscillating body, extracting energy through flutter (Olivieri et al., 2017). Alternatively, the geometry serves as an auxiliary element that generates or modifies the wake to enhance the performance of a downstream harvester (Liu et al., 2020).

In this study, a flat plate with an inclination angle of 30° is investigated using a Computational Fluid Dynamics (CFD) approach. The main objective is to evaluate the energy harvesting potential of the plate by attaching a semicircular cylinder to the lower surface of the plate. The semicircular cylinder is therefore positioned at the leading edge, the mid-chord, and the trailing edge, and the corresponding effects on the aerodynamic forces, shedding frequency, and wake structure are investigated.

MATERIALS AND METHODS

The numerical simulations were performed using the open-source CFD software OpenFOAM v2406. The geometry was a sharp-edged inclined flat plate at an inclination angle of 30°, with a chord length of $c = 0.15$ m and a thickness of 3% of the chord. The two-dimensional computational domain was rectangular, with an upstream length of 8c and a downstream length of 20c. The upper and lower boundaries of the domain were located 15c from the plate, as shown in Figure 1. All outer boundaries of the computational domain were assigned the freestream condition, enforcing the free-stream value on inflow and a zero-gradient condition on outflow (OpenCFD Ltd., 2024). The free-stream velocity was set to $U_\infty = 15$ m/s, and the kinematic viscosity was $\nu = 1.5 \times 10^{-5}$ m²/s, corresponding to a chord-based Reynolds number of 1.5×10^5, consistent with the reference studies used for validation. A no-slip boundary condition was applied on the plate surface.

The fluid flow was considered two-dimensional, incompressible and unsteady state. For turbulence modelling, SST k-ω was employed. Pressure-velocity coupling was achieved using the PIMPLE algorithm, which combines the PISO (Pressure Implicit with Splitting of Operators) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms. A constant time step verified through a

time-step independence study, was employed to ensure that the Courant number remained below unity ($Co \leq 1$) in each simulation.

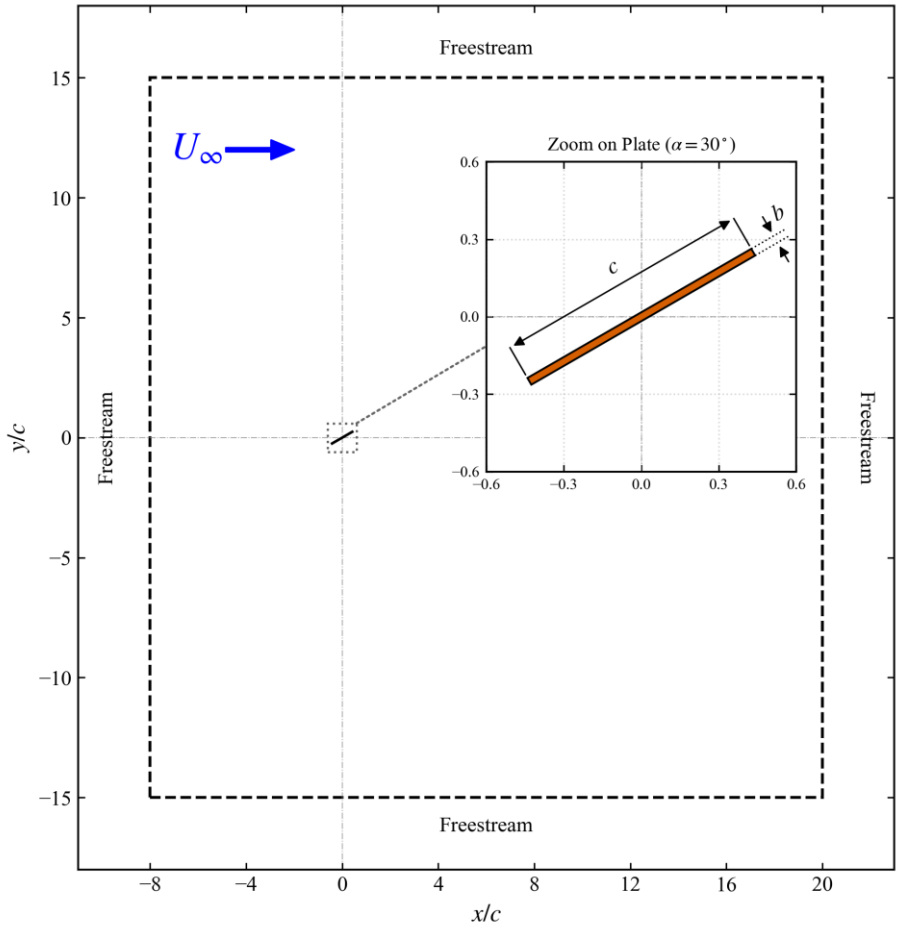


Figure 1. Computational domain and boundary conditions.

Following the numerical setup, the mesh independence and time-step independence tests were performed. Four grids of varying resolution, with the number of elements ranging from 55,000 to 460,000, were generated using SALOME (version 9.15.0) to evaluate the sensitivity of the results to mesh refinement. Furthermore, the time step independence tests were conducted considering time-step sizes of 2×10^{-5} s, 1×10^{-5} s, 5×10^{-6} s and 2×10^{-6} s. The results of the independence analysis are presented in the Findings and Discussion section.

Based on the Strouhal number of approximately 0.307 reported for a 30° inclined plate in the literature (Fage and Johansen, 1927), the shedding frequency for the present flow conditions was estimated to be approximately 30 Hz. This corresponds to a shedding period of about 0.033 s, so that the 1.0 s simulated period covers roughly 30 vortex-shedding cycles. In previous numerical studies of bluff-body wakes, the flow is reported to reach a statistically steady state after approximately ten shedding cycles (Kumar Pant et al., 2026). The simulation period adopted here is therefore about three times longer, which ensured that the initial transient had fully decayed and that the statistics were converged. Accordingly, the time-averaged drag and lift coefficients and the corresponding RMS values were computed from 0.40 s onwards.

The mesh and time-step independence studies were performed for the baseline plate, and the selected mesh and time step were subsequently applied to all modified configurations to ensure a consistent basis for comparison. A semicircular cylinder with a non-dimensional diameter of d* = d/c = 0.14 was attached to the lower surface of the plate. Three positions of the cylinder were considered, which are tangent to the leading edge (V1), at the mid-chord (V2), and tangent to the trailing edge (V3), as shown in Figure 2.

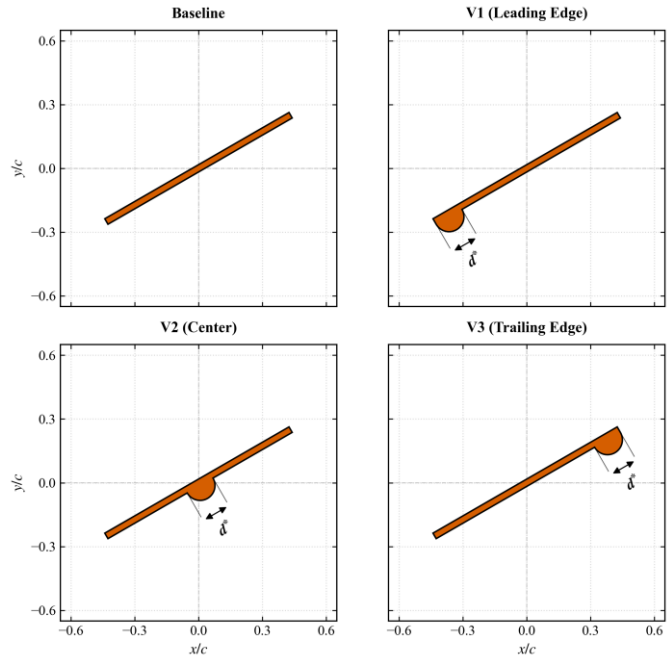


Figure 2. Schematic of the baseline plate and the three positions of the semicircular cylinder.

FINDINGS AND DISCUSSION

In this section, the numerical setup is first verified through mesh and time-step independence studies and validated against experimental and numerical data from the literature. Second, the influence of the semicircular cylinder position on the aerodynamic loads and wake structure is discussed.

The mesh independence tests were conducted to assess the sensitivity of the numerical results to the grid, as mentioned in the previous section. Mesh structures with different numbers of elements were evaluated in terms of the time-averaged drag and lift coefficients, as shown in Figure 3. The time-averaged drag coefficient is in the range of 0.858 to 0.898. The magnitude of the time-averaged lift coefficient increases gradually from 1.342 to 1.401. The differences between M3 (253×10³ cells) and M4 (460×10³ cells) are 0.12% for $\bar{C}_D$ and 0.5% for $|\bar{C}_L|$. The results indicate that further grid refinement has a negligible effect on the aerodynamic loads. As a result, M3 was selected, for the simulations to ensure accuracy at a reasonable computational cost. The grid structure of M3 is shown in Figure 4.

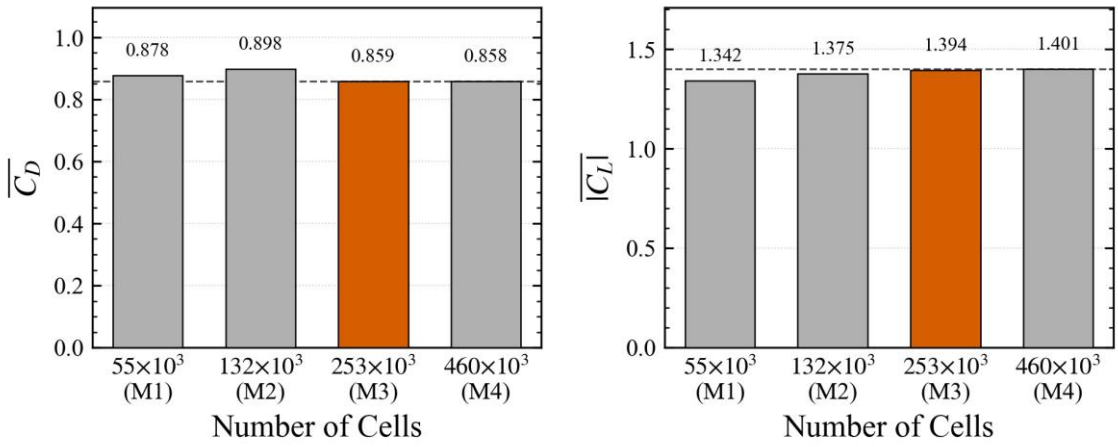


Figure 3. Mesh independence test results.

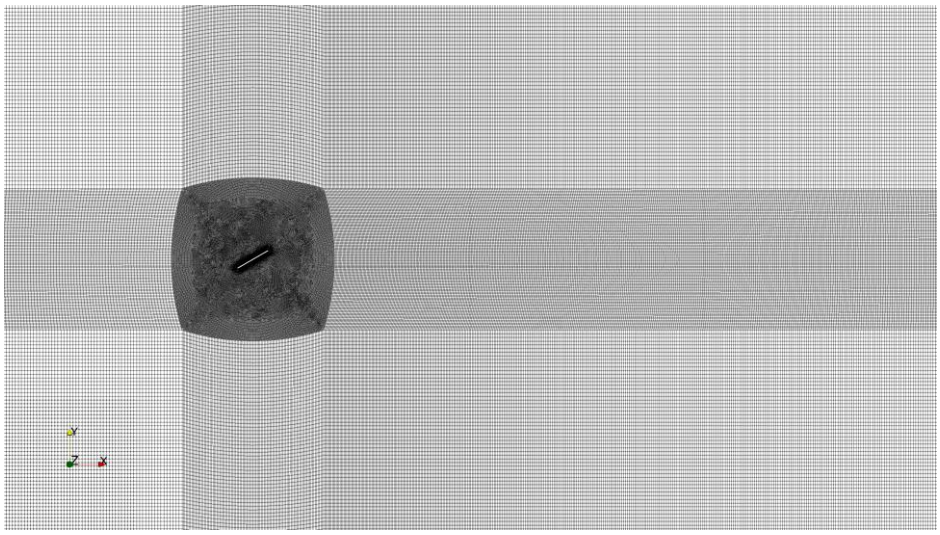


Figure 4. Computational grid used in the simulations.

The time-step independence tests were conducted using four time-step sizes, and the results are presented in Figure 5. Both the time-averaged drag and lift coefficients increase as the time step is reduced. A time-step size of 5×10^{-6} s was adopted, since the variation between Δt_3 and Δt_4 is less than 2% for both coefficients. This temporal resolution is considered sufficient to accurately capture the unsteady flow dynamics and wake characteristics behind the inclined plate.

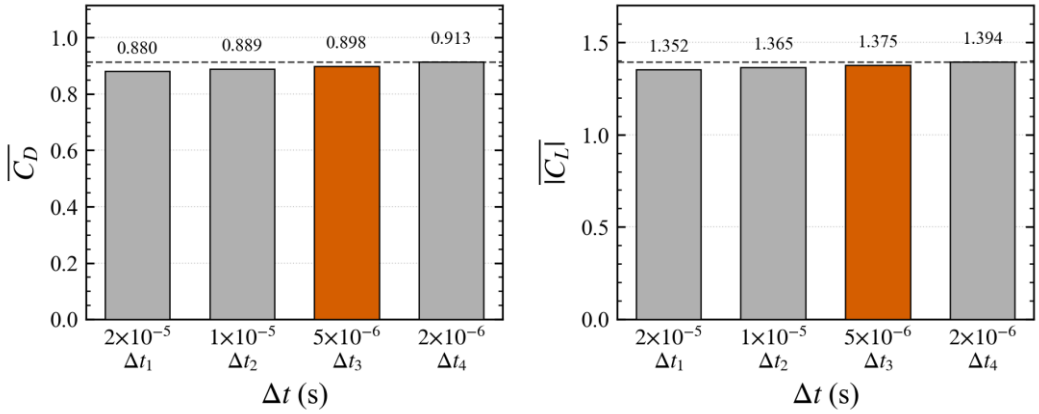


Figure 5. Time-step independence test results.

After the independence studies, the numerical setup was validated against the experimental data of Fage and Johansen (1927) and the Large Eddy Simulation (LES) results of Shademan and Naghib-Lahouti (2020). Figure 6 shows the time-averaged pressure coefficient distribution along the upper surface, where C_p decreases from about 1.0 at the leading edge towards the trailing edge, and along the lower surface, which exhibits a nearly uniform negative C_p plateau. The present results show excellent agreement with the experimental data throughout the upper surface. On the other hand, the present numerical model predicts slightly higher-pressure coefficients than the LES. On the lower surface, a nearly uniform pressure plateau is observed for both the results of the present study and the literature. However, the results indicate that pressure coefficients on the lower surface of the plate from the present study are considerably lower compared to the literature. This overprediction of the suction on the lower surface is a known limitation of two-dimensional simulations, in which the absence of spanwise vortex stretching leads to stronger and more coherent vortices in the near wake.

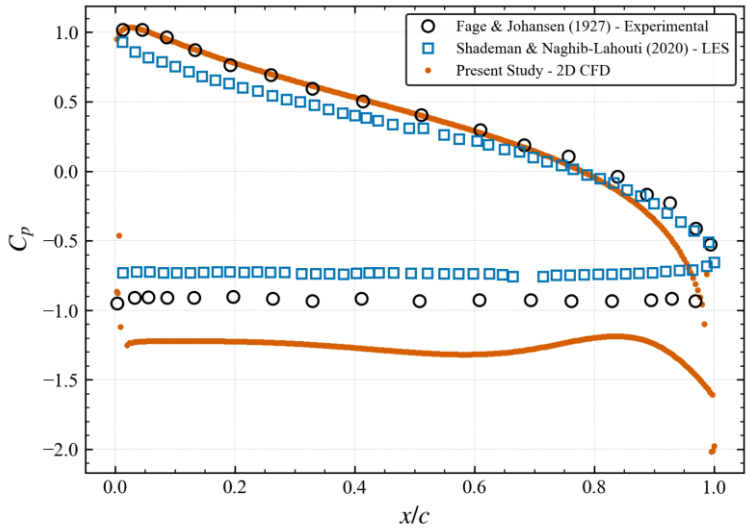


Figure 6. Validation of the time-averaged pressure coefficient along the plate.

The time-averaged drag and lift coefficients, the RMS lift coefficient and the Strouhal number of the baseline plate and the three configurations are given in Table 1. The mean force coefficients are almost unaffected by the position of the semicircular cylinder. Both the mean drag and the mean absolute lift coefficients change by less than 2% in all configurations. On the other hand, the RMS lift coefficient is highly influenced by the position of the element. In the V2 configuration, the RMS lift coefficient decreases by 10.5%, while an increase of 8.9% is observed for the V3 case.

Table 1. Aerodynamic coefficients of the baseline plate and the three configurations.

Case	$\overline{C_D}$ [−]	$\overline{\lvert C_L \rvert}$ [−]	$C_{L_{rms}}$ [−]	St [−]	$C_{L_{rms}}$ ϵ [%]
Base	0.8588	1.3937	0.1792	0.344	-
V1	0.8537	1.4056	0.1781	0.347	-0.6
V2	0.8418	1.3928	0.1604	0.350	-10.5
V3	0.8668	1.3928	0.1952	0.335	+8.9

The time-averaged streamlines are presented in Figure 7 to gain a better understanding of the flow characteristics around the plate. The flow separation is observed at the sharp leading edge and a large recirculation region is created on the lower side of the plate for all configurations. The recirculation region and the secondary vortex of V1 are almost identical to those of the baseline plate. In the V2 and V3 configurations, the streamline pattern inside the recirculation region differs from that of the baseline plate, whereas the secondary vortex remains at almost the same position. The overall mean flow topology is therefore preserved, which is consistent with the small changes in the mean loads given in Table 1.

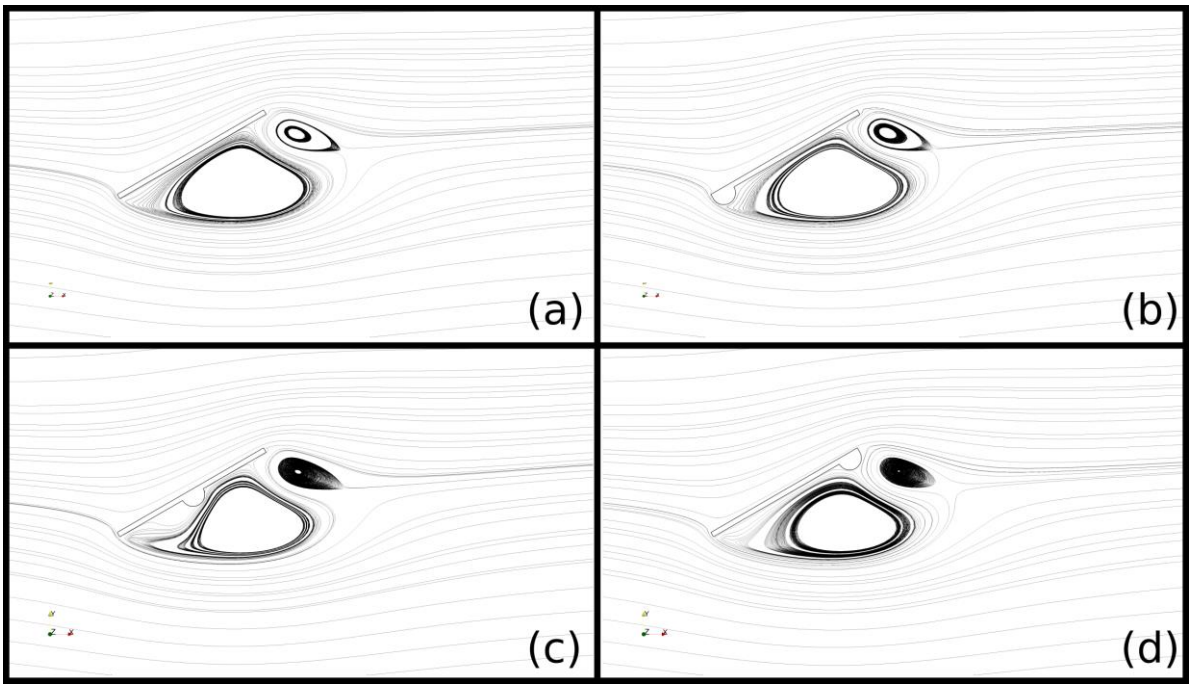


Figure 7. Time-averaged streamlines (a) Base, (b) V1, (c) V2, (d) V3.

Figure 8 shows the time history of the lift coefficient, which is negative in the adopted coordinate system. For this reason, the mean lift is given as an absolute value in Table 1. The baseline plate and V1 produce similar signals. On the other hand, the periodic regime rapidly becomes stable, and the amplitude of the lift coefficient is lower in the V2 configuration. Moreover, the lift coefficient signal remains irregular until flow time 0.30 s and the amplitude in the periodic regime is higher than in the other cases for the V3 case. These observations agree with the RMS lift coefficient values in Table 1.

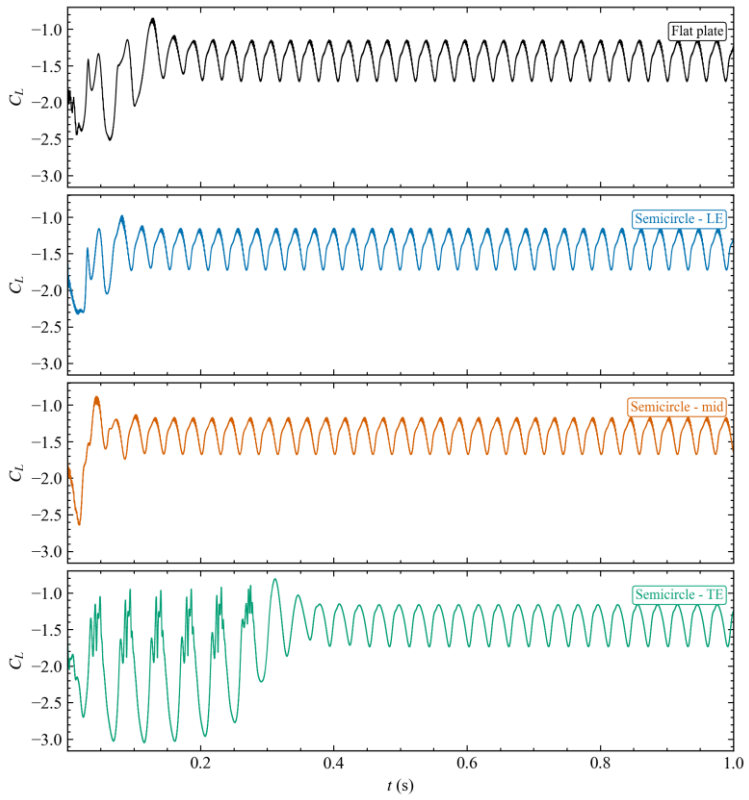


Figure 8. Time histories of the lift coefficient.

Figure 9 compares the vorticity fields at a flow time of 0.20 s. The wakes of the baseline plate and V1 have already formed a regular vortex street and are very similar to each other. The wake of V2 has also reached periodic shedding and has the most uniform vortex spacing. In contrast, the wake of V3 remains irregular and asymmetric. Moreover, periodic vortex shedding is observed for all configurations when the flow time reaches 1 s, as shown in Figure 10. Similar to the case at a flow time of 0.2 s, the wake of V1 is identical to that of the baseline plate at 1 s. On the other hand, the vortices behind the V2 plate have a more compact form near the body. In addition, a longer shear layer rolls up into a larger vortex close to the body in the V3 configuration. The differences are confined to the near wake, and the vortex spacing in the far wake is nearly identical in all cases.

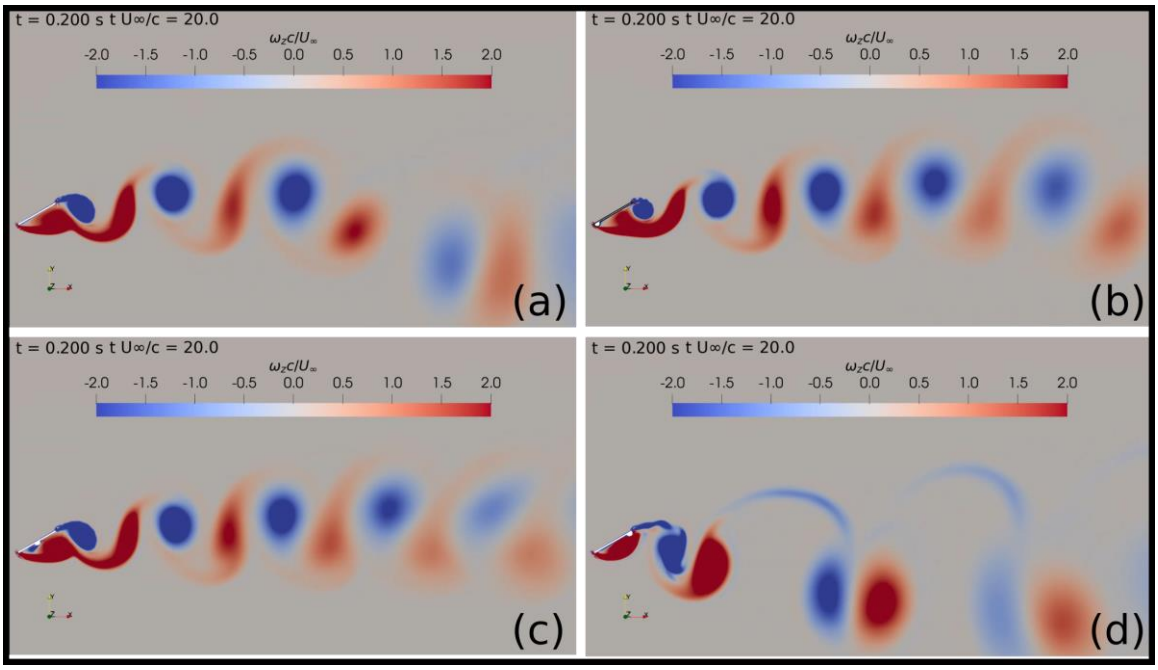


Figure 9. Instantaneous vorticity at a flow time of 0.20 s: (a) Base, (b) V1, (c) V2 and (d) V3.

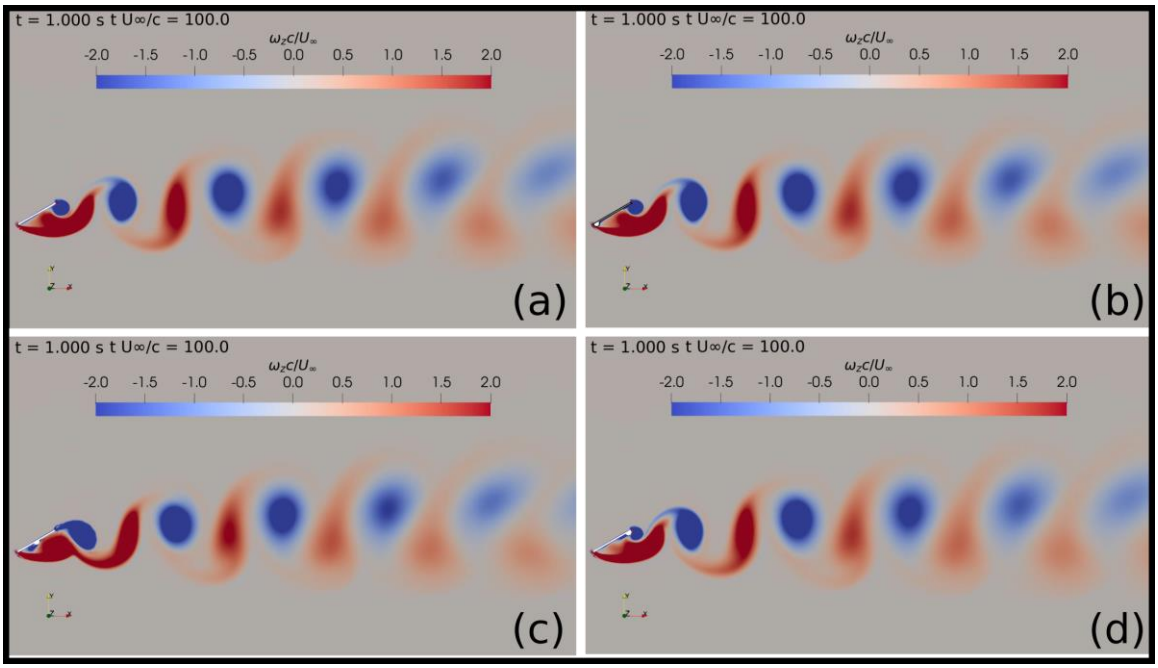


Figure 10. Instantaneous vorticity at a flow time of 1.0 s: (a) Base, (b) V1, (c) V2 and (d) V3.

CONCLUSION AND RECOMMENDATIONS

In this study, the unsteady flow around a 30° inclined flat plate at a Reynolds number of 1.5×10^5 was numerically investigated. The effect of the position of a semicircular cylinder attached to the lower surface of the plate was evaluated. The position of the element changed the lift fluctuations. However, the mean aerodynamic forces varied by less than 2% in all configurations. First, the element was placed at the leading edge (V1) and the forces, and the wake region remained almost the same as those of the flat plate. In the V2 case, the near wake was stabilised, the periodic regime was reached earlier and the RMS lift coefficient decreased by 10.5%. This configuration is therefore a promising solution for suppressing vortex-induced vibrations. At the trailing edge (V3), the RMS lift coefficient increased by 8.9% and larger vortices formed in the near wake at a slightly lower Strouhal number. The stronger lift fluctuation provides a larger excitation for a flexible structure, which indicates a potential for enhancing flow-induced energy harvesting.

Future work should include three-dimensional effects and a coupled fluid–structure interaction model to quantify the vibration response and to analyse energy harvesting potential.

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INVESTIGATION OF PRODUCING COMPOSITE MATERIALS FROM WASTE ALUMINUM AND CUSN10 BRONZE CHIPS BY HOT EXTRUSION

ATIK ALÜMİNYUM VE CUSN10 BRONZ TALAŞLARINDAN SICAK EKSTRÜZYONLA KOMPOZİT MALZEME ÜRETİMİNİN ARAŞTIRILMASI

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Abstract
Machining processes provide high dimensional accuracy and surface quality in industrial manufacturing; however, they also generate considerable amounts of metallic chips. The efficient recovery of chips originating from economically valuable metals and alloys such as aluminum and bronze is important for reducing raw material consumption and developing sustainable manufacturing processes. Conventional metal recycling methods are largely based on remelting and may involve disadvantages such as high energy consumption, oxidation-related material losses, and the need for additional processing steps. For this reason, solid-state recycling methods based on the direct reshaping of metallic chips without melting have attracted increasing attention as an alternative approach.
In this study, the direct recycling of waste aluminum and CuSn10 bronze chips generated during machining processes by hot extrusion and their feasibility for composite material production will be investigated. Prior to processing, cleaning procedures will be applied to remove oil, dirt, and machining residues from the chip surfaces. The chips will then be dimensionally classified in order to evaluate the effect of different particle sizes on consolidation behavior. The prepared aluminum and CuSn10 bronze chips will be homogenized at different mixing ratios and subjected to hot extrusion at approximately 400–425 °C under pressures of about 270–300 MPa. The high plastic deformation imposed during extrusion is expected to enhance inter-chip contact and promote the formation of metallic bonding between the consolidated particles.
Various tests will be conducted to determine the physical and mechanical integrity of the produced samples. The effects of chip size, mixing ratio, and extrusion parameters on material integrity and mechanical behavior will be comparatively evaluated. The study aims to demonstrate the feasibility of converting waste Al and CuSn10 chips with different physical and mechanical characteristics into an integrated composite structure by hot extrusion without remelting, and to contribute to the development of a sustainable manufacturing approach for transforming metallic machining waste into value-added engineering materials.
Keywords: Recycling, waste metals, composite

Özet
Talaşlı imalat yöntemleri, endüstriyel üretimde yüksek boyutsal hassasiyet ve yüzey kalitesi sağlamasına karşın önemli miktarda metal talaşı oluşmasına neden olmaktadır. Özellikle alüminyum ve bronz gibi ekonomik değeri yüksek metal ve alaşımlardan oluşan talaşların etkin biçimde geri kazanılması, hammadde kullanımının azaltılması ve sürdürülebilir üretim süreçlerinin geliştirilmesi açısından önem taşımaktadır. Geleneksel metal geri dönüşüm yöntemleri büyük ölçüde ergitme esasına dayanmakta olup yüksek enerji tüketimi, oksidasyon kaynaklı malzeme kayıpları ve ilave işlem gereksinimleri gibi bazı dezavantajlara sahiptir. Bu nedenle, metal talaşlarının ergitilmeden doğrudan yeniden şekillendirilmesine dayanan katı hâlde geri dönüşüm yöntemleri alternatif bir yaklaşım olarak değerlendirilmektedir.
Bu çalışmada, talaşlı imalat işlemleri sonucunda ortaya çıkan atık alüminyum ve CuSn10 bronz talaşlarının sıcak ekstrüzyon yöntemi kullanılarak doğrudan geri dönüştürülmesi ve kompozit malzeme üretiminde kullanılabilirliğinin araştırılması amaçlanmaktadır. Üretim öncesinde talaş yüzeylerinde bulunabilecek yağ, kir ve işlem kalıntılarının giderilmesi amacıyla temizleme işlemleri uygulanacak, ardından talaşlar boyutsal olarak sınıflandırılarak farklı tane boyutlarının konsolidasyon davranışına etkisi değerlendirilecektir. Hazırlanan alüminyum ve CuSn10 talaşları farklı karışım oranlarında homojenleştirilecek ve yaklaşık 400–425 °C sıcaklık aralığında, 270–300 MPa seviyelerinde sıcak

ekstrüzyon işlemine tabi tutulacaktır. Ekstrüzyon sırasında uygulanan yüksek plastik deformasyon sayesinde talaşlar arasındaki temasın ve metalik bağ oluşumunun geliştirilmesi hedeflenmektedir. Üretilen numunelerin fiziksel ve mekanik bütünlüğünün belirlenmesi amacıyla farklı testler yapılacaktır. Elde edilen veriler kullanılarak talaş boyutu, karışım oranı ve ekstrüzyon parametrelerinin malzeme bütünlüğü ve mekanik davranış üzerindeki etkileri karşılaştırmalı olarak değerlendirilecektir. Çalışmanın sonucunda, farklı fiziksel ve mekanik özelliklere sahip atık Al ve CuSn10 talaşlarının ergitme işlemi uygulanmaksızın sıcak ekstrüzyonla bütüncül bir kompozit yapıya dönüştürülebilirliğinin ortaya konulması ve metal talaşlarının katma değerli mühendislik malzemelerine dönüştürülmesine yönelik sürdürülebilir bir üretim yaklaşımının geliştirilmesi hedeflenmektedir.

Anahtar kelimeler: Geri dönüşüm, atık metaller, kompozit

CONTEXT-AWARE MACHINE LEARNING FOR ANOMALY DETECTION IN NANOINDENTATION CURVES: SAMPLE-GROUPED VALIDATION

NANOİNDENTASYON EĞRİLERİNDE BAĞLAM DUYARLI MAKİNE ÖĞRENMESİYLE ANOMALİ TESPİTİ: NUMUNE-GRUPLU DOĞRULAMA

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ABSTRACT

High-throughput nanoindentation generates load-displacement curves at scale, making manual anomaly screening impractical. This study tested whether sample-relative contextual descriptors improve prediction of expert-labelled anomalies in a post-acquisition batch setting. We analysed an open dataset of 9,600 curves from 150 electrodeposited NiFe thin-film samples; 3,409 curves (35.5%) were labelled anomalous in the revised annotations. Predictors comprised instrument-derived summary properties, hand-crafted curve-shape features describing loading, holding, unloading, and residual-depth behaviour, and sample-relative contextual descriptors computed from the other 63 curves without using anomaly labels. Logistic regression, random forest, and histogram gradient boosting were evaluated with fixed settings using five-fold sample-grouped cross-validation, with all 64 indentations from each sample kept in one fold. Balanced accuracy was the primary metric; results are mean ± SD across folds. Adding contextual descriptors increased mean balanced accuracy for all three model families, with random forest giving the highest mean value. For random forest, summary properties alone achieved 0.767 ± 0.011 balanced accuracy, curve-shape features 0.927 ± 0.017, and combined summary-plus-curve features 0.928 ± 0.015. Adding contextual descriptors increased balanced accuracy to 0.936 ± 0.013 and F1-score to 0.925 ± 0.013, with positive gains in all five grouped folds. Random curve-level validation using the same combined summary-plus-curve features without contextual descriptors gave a slightly higher estimate than sample-grouped validation (0.938 versus 0.928). For the same random-forest contextual configuration, excluding the 11 fully anomalous samples yielded similar balanced accuracy (0.935 ± 0.016). Full curve-shape information was more predictive than standard summary properties, while sample-relative contextual descriptors provided a smaller, directionally consistent gain within this NiFe dataset. Because reference labels were assigned while all 64 curves from each sample were viewed together, the context gain may partly reflect expert comparative labelling rather than independent physical evidence. External validation on other material systems or acquisition setups was not performed.

Keywords: nanoindentation, anomaly detection, machine learning, load-displacement curves, sample-grouped cross-validation

ÖZET

Yüksek verimli nanoindentasyon çok sayıda yük-yer değiştirme eğrisi üretmekte ve manuel anomali taramasını büyük ölçekte güçleştirmektedir. Bu çalışmada, numune-içi göreli bağlamın ölçüm sonrası toplu değerlendirmede uzman etiketli anomalilerin tahminini iyileştirip iyileştirmediği incelenmiştir. Elektrokaplama ile üretilmiş 150 NiFe ince film numunesinden elde edilen 9.600 eğriyi içeren açık veri setinde, güncellenmiş uzman etiketlerine göre 3.409 eğriye (%35,5) anomali etiketi verilmiştir. Tahmin değişkenleri; cihazdan elde edilen özet özellikler, yükleme, bekletme, boşaltma ve kalıcı derinlik davranışlarını tanımlayan öznitelik mühendisliği ile türetilmiş eğri-şekil özellikleri ve anomali etiketleri kullanılmadan aynı numunedeki diğer 63 eğriden hesaplanan numune-içi bağlam tanımlayıcılarından oluşturulmuştur. Lojistik regresyon, rastgele orman ve histogram tabanlı gradyan artırma modelleri, önceden belirlenmiş ayarlarla beş katlı numune-gruplu çapraz doğrulama kullanılarak değerlendirilmiş; aynı numuneye ait 64 indentasyon aynı katta tutulmuştur. Birincil performans ölçütü dengeli doğruluk olarak belirlenmiş ve sonuçlar ortalama ± standart sapma olarak verilmiştir. Bağlamın eklenmesi üç model ailesinde de ortalama dengeli doğruluğu artırmış, en yüksek ortalama rastgele ormanda elde edilmiştir. Rastgele ormanda özet özellikler 0,767 ± 0,011, eğri-şekil özellikleri 0,927 ± 0,017 ve bunların birleşimi 0,928 ± 0,015 dengeli doğruluk sağlamıştır. Bağlam eklendiğinde dengeli doğruluk

0,936 ± 0,013'e, F1 skoru 0,925 ± 0,013'e yükselmiş ve artış beş katın tamamında pozitif olmuştur. Aynı bağlamsız özet ve eğri özellikleriyle rastgele eğri-düzeyi doğrulama, numune-gruplu doğrulamadan biraz daha yüksek bir tahmin vermiştir (0,938'e karşı 0,928). 64 eğrisinin tamamına anomali etiketi verilmiş 11 numune çıkarıldığında performans benzer kalmıştır (0,935 ± 0,016). Bulgular, tam eğri-şekil bilgisinin standart özet özelliklerden daha yüksek tahmin değeri taşıdığını ve numune-içi bağlamın bu NiFe veri setinde daha küçük fakat yön açısından tutarlı bir katkı sağladığını göstermektedir. Ancak referans etiketleri her numunedeki 64 eğri birlikte görülerek oluşturulduğundan, bağlam katkısı bağımsız fiziksel kanıttan ziyade uzmanların karşılaştırmalı etiketleme yaklaşımını kısmen yansıtıyor olabilir. Farklı malzeme sistemleri veya ölçüm düzeneklerinde dış doğrulama yapılmamıştır.
Anahtar kelimeler: nanoindentasyon, anomali tespiti, makine öğrenmesi, yük-yer değiştirme eğrileri, numune-gruplu çapraz doğrulama

1. INTRODUCTION

The load–displacement response recorded during instrumented nanoindentation provides an established basis for estimating hardness and reduced modulus at small length scales (Oliver & Pharr, 1992, 2004). Bassett et al. (2023) combined high-throughput nanoindentation with other characterization techniques to study combinatorial sets of electrodeposited films. The present analysis uses published data from 150 electrodeposited NiFe samples, each contributing 64 load–displacement curves, for a total of 9,600 curves with expert annotations (Zakariya, Babuska, Mundt, & Henriksen, 2026). The workload associated with expert review motivates machine-assisted anomaly screening for nanoindentation quality control (Zakariya et al., 2026).

Kossman and Bigerelle (2021) trained a convolutional neural network to identify pop-in events in nanoindentation curves. For a different prediction target, Trost et al. (2025) classified and clustered nanoindentation data from high-speed steel and found that feature engineering with curve-derived descriptors improved model performance. These studies support examining curve-derived predictors, while the additional value of within-sample context for distinguishing anomalous from normal curves remains a separate empirical question.

In the NiFe dataset, the expert labelling process included joint viewing of the 64 curves from a physical sample, and the authors explicitly discuss potential per-sample bias (Zakariya et al., 2026). A contextual model is therefore evaluated against judgements formed through a process that itself used sample context. Validation must also reflect the intended prediction target: for hierarchically structured data, performance on new groups is a different question from performance on additional observations within represented groups (Roberts et al., 2017). Here, the relevant group is the physical sample.

This study evaluates whether label-free, sample-relative features improve binary classification of expert-labelled nanoindentation curves beyond individual-curve information when testing on previously unseen physical samples within this NiFe dataset. The comparison adds within-sample context to the same set of individual-curve predictors and keeps all indentations from each physical sample together during validation. Random indentation-level validation serves as a comparator. The intended application is post-acquisition quality control: after all 64 curves from a sample have been acquired, each curve is described relative to the other 63 curves without using their labels. This is a batch setting with transductive context from the unlabelled test-sample curves. The study includes no external validation, so its conclusions concern agreement with the contextual expert labels within this dataset.

2. MATERIALS AND METHODS

2.1. Study design and data provenance

This study used the open nanoindentation dataset described by Zakariya et al. (2026) for secondary machine-learning analysis. The experimental measurements and expert annotations were produced by the original investigators. No new specimens, indentation experiments, or expert annotations were generated for the present study. The dataset contains 150 physical electrodeposited NiFe samples drawn from the characterization study of Bassett et al. (2023), with 64 indentation curves per sample and 400 recorded points per curve. The data are deposited in the Materials Data Facility (Henriksen, Zakariya, Babuska, & Mundt, 2025).

2.2. Dataset assembly and binary target

The revised annotations were read from updated_all_samples_labelled.csv. Records were matched to the modelling table using sample_num and indent_num, yielding 9,600 one-to-one matches with no duplicate keys or unmatched records. All raw-curve paths listed in the annotation file were present in the archive. The binary target was 1 (anomalous) if any of seven revised annotation fields was greater than zero and 0 (normal) otherwise. The fields were fully anomalous sample, force offset, displacement offset, unusual unloading curvature, unusual loading curvature, tip displacement decreases at holding, and too deep. All positive severity levels were included, including level 1, which denotes borderline or less certain annotations in the source taxonomy (Zakariya et al., 2026). This rule yielded 3,409 anomalous and 6,191 normal curves, corresponding to an anomaly prevalence of 35.5%. Recalculation from the annotation fields reproduced every target value in the modelling table.

The categories could overlap and were not treated as mutually exclusive classes. The other text field did not contribute to the binary target; all 31 non-empty, non-zero entries already had a positive taxonomy annotation. The source study used feature-based consistency checks to select curves for expert reinspection, producing the revised annotations. Both initial annotation and reinspection allowed access to within-sample visual context (Zakariya et al., 2026). The prediction target consequently represents contextual expert assessments rather than independently established physical causes.

2.3. Individual-curve features

Four feature sets were compared. Set A comprised ten instrument-reported summaries supplied with the dataset: contact depth, maximum load, stiffness, maximum displacement, effective depth, reduced modulus, hardness, unloading coefficient, final displacement, and unloading exponent. The values were taken from the released per-sample summary files. Their equality to the corresponding modelling-table entries was verified for all 9,600 indentations. These values were retained as predictors of expert labels; their inclusion does not establish that each anomalous curve yields a physically valid mechanical-property estimate. Drift and projected contact area were not included in Set A.

Set B contained 33 descriptors computed from individual depth, load, and time records. Let h_j, P_j, and t_j denote the recorded depth, load, and time at point j. For each curve, the first and last indices satisfying $P_j \geq 0.98$ max(P) were designated a and b. The loading segment comprised points 0 through a, the hold segment a through b, and the unloading segment b through the final point, including the boundary points in both adjacent segments. Feature definitions used these data-derived boundaries rather than assuming a fixed duration for each segment.

Initial load and depth were the medians of the first five recorded points. Maximum load and depth were the respective maxima over the curve, and final load and depth were the last recorded values. Timing descriptors were t_a, t_b, and $t_b - t_a$. Loading work was the signed trapezoidal integral of load with respect to depth over the loading segment; unloading work was the absolute value of the corresponding unloading integral. Their ratio was $W_{unload}/(|W_{load}| + 10^{-9})$, using the recorded units of micronewtons and nanometres. These integrals were used as curve descriptors without asserting a physical energy interpretation for every anomalous trace.

Three monotonicity descriptors measured the fractions of consecutive depth changes that were negative during loading, positive during unloading, or negative during the hold. Hold-depth and hold-load changes were the respective medians of the last ten points minus the medians of the first ten points within the hold segment. Loading-terminal and unloading-initial slopes were obtained by fitting a straight line to load as a function of depth using, respectively, the last 25 loading points and first 25 unloading points. For each loading and unloading segment, depth and load were separately mapped to [0, 1] using that segment's minimum and range. A quadratic was fitted to normalized load as a function of normalized depth, and its root-mean-square residual was retained as a shape descriptor.

At 20%, 40%, 60%, and 80% of the curve's maximum load, the recorded point with the closest load was selected separately within the loading and unloading segments. The two depths and their difference, unloading minus loading, provided twelve further descriptors. These were nearest-recorded-point features, not interpolated depths. Set C combined Sets A and B, giving 43 individual-curve predictors. The instrument-reported maxima in Set A and the maxima recomputed from raw curves in Set B were retained as separate predictors.

2.4. Label-free within-sample context

Set D added 20 contextual descriptors to Set C. Context was constructed from ten quantities: initial load, initial depth, maximum depth, final depth, hardness, reduced modulus, stiffness, hold-depth change, loading quadratic residual, and unloading quadratic residual. For a quantity x belonging to indentation i, the reference comprised the other 63 indentations from the same physical sample. The reference median and median absolute deviation were

m_{-i} = median{x_j : j belongs to the same sample, j ≠ i},

MAD_{-i} = median{$|x_j - m_{-i}|$: j belongs to the same sample, j ≠ i}.

Two descriptors were retained for each quantity:

$z_i = (x_i - m_{-i})/(1.4826\ MAD_{-i} + 10^{-9})$, and $|z_i|$.

The factor 1.4826 scales MAD to the standard-deviation scale under a normal distribution; its use does not assume that the within-sample values are normally distributed. The same numerical value, 10^{-9}, was added to every denominator in the recorded units of the respective quantity, without adapting it to that quantity's typical magnitude. Where the reference MAD was zero, the denominator was therefore 10^{-9}; the resulting descriptors were retained without clipping, with absolute values reaching approximately 2.85×10^9 for initial-depth context. Neither reference construction nor selection of reference curves used anomaly labels or a known-normal subset. The reference statistics therefore describe the sample's mixture of curves and do not necessarily represent normal behaviour. In the 11 samples for which all 64 curves were labelled anomalous, each reference consisted of 63 curves carrying anomalous labels. Their contextual descriptors therefore measure within-sample deviations without a normal-labelled reference. All 64 curves from a sample were assumed available before prediction. Thus, when a sample was held out during validation, its contextual predictors used its own unlabelled curves. This is a post-acquisition batch setting with transductive context. It does not describe prediction from a single isolated indentation. The archived modelling table contained 63 finite, non-constant feature columns. Sample and indentation identifiers were retained for record matching and grouping but were not predictors. Expert notes, other, annotation fields, batch and processing metadata, dates, stage coordinates, point counts, and voltage channels were also excluded as predictors. These exclusions restrict obvious routes for identity- or annotation-based prediction; they do not establish the absence of every possible shortcut.

2.5. Models and computational provenance

Logistic regression (LR), Random Forest (RF), and histogram gradient boosting (HGB) were implemented in scikit-learn (Pedregosa et al., 2011). The documented verification analysis used fixed settings without a hyperparameter search or decision-threshold optimization. Logistic regression used training-fold standardization, L2 regularization, C = 1, the liblinear solver, balanced class weights, random_state = 42, and max_iter = 5000. Standardization parameters were fitted using each training fold and applied to its held-out fold. No imputation was required because the archived feature matrix contained no missing or infinite values. Random Forest and histogram gradient boosting used the unscaled feature matrix.

Random Forest used 120 trees, a minimum of two samples per leaf, balanced_subsample class weights, and random_state = 42. Other structural settings followed scikit-learn 1.8.0 defaults, including Gini impurity, square-root feature subsampling, bootstrap sampling, and no maximum tree depth. Histogram gradient boosting used balanced class weights and random_state = 42 with scikit-learn 1.8.0 defaults: log loss, learning rate 0.1, 100 boosting iterations, at most 31 leaves, at least 20 samples per leaf, no maximum depth, and zero L2 regularization. With early_stopping='auto', fewer than 10,000 observations in each training fold, and no separate validation data supplied to fit, this comparator did not invoke an internal early-stopping validation split. Discrete predictions were obtained using each classifier's predict method; probabilities for class 1 were retained for probability-based metrics.

Historical implementation provenance was incomplete. The original execution script was not available in the retrieved archive. The Random Forest specification was reconstructed by comparison with archived fold-level outputs; it is a numerical fingerprint reconstruction, not recovery of the original code. The logistic-regression verification implementation is likewise explicitly recorded rather than asserted to be the original constructor. The exact historical histogram-gradient-boosting constructor could not be recovered. Its fully specified rerun is therefore reported as a reproducible full-paper comparator, separately from historical results. Reconstruction of historical settings was not presented as an independent model-selection experiment.

2.6. Validation and context ablation

Primary evaluation used five-fold StratifiedGroupKFold with shuffle=True and random_state=42, grouping on the physical sample identifier. Every indentation from a sample was assigned to the same held-out fold. Fold membership was checked for disjoint training and test sample sets. The intended generalization target was previously unseen physical samples within this dataset. Sample grouping prevents indentations from the same physical sample being divided between training and testing; it does not establish independence across fabrication conditions or laboratories.

The same grouped folds and model settings were used across feature sets. The contribution of context was assessed by comparing Set D with Set C for each model and computing paired fold differences. In the documented verification run, a separate Random Forest comparison used Set C under five-fold StratifiedKFold with shuffle=True and random_state=42 at the indentation level. Context features were excluded from this split comparison. Because the random split can place curves from the same physical sample in both training and testing, it addresses a different prediction setting and was treated as a comparator rather than the principal estimate for unseen samples.

2.7. Performance measures and robustness analyses

Balanced accuracy (BA) was specified as the primary performance measure because the binary target was imbalanced, and F1 for the anomalous class was used as the principal secondary measure. If TP, TN, FP and FN denote the true-positive, true-negative, false-positive and false-negative counts, respectively, balanced accuracy was calculated as [TP/(TP+FN) + TN/(TN+FP)]/2 and anomalous-class F1 as 2TP/(2TP+FP+FN). Each curve had unit weight in the confusion-matrix counts; BA then weighted the two class recalls equally. For every model-feature configuration, fold scores were summarized by their unweighted mean and sample standard deviation across the five held-out folds. Precision, recall, area under the receiver operating characteristic curve (ROC-AUC), and average precision were retained as supporting measures. Average precision summarized the precision–recall steps without trapezoidal interpolation.

The incremental contribution of context was evaluated from paired Set D minus Set C differences on the same grouped folds. The direction of each fold difference was recorded as a descriptive check; the five folds were not treated as independent replications, and no formal paired significance test was performed. For the annotation-level description, out-of-fold predictions from the grouped Random Forest Set D model were matched to each positive annotation field. The resulting subtype recall was the proportion of curves carrying a given annotation that received an anomalous binary prediction. Because annotations could overlap, these calculations were not interpreted as a multiclass confusion matrix or as independent class-specific performance estimates.

Three post-hoc robustness analyses were conducted without performance-based hyperparameter tuning or classification decision-threshold optimization. First, the 20 contextual columns in Set D were symmetrically clipped at -100 and +100, and then at -10 and +10. Set C, the 43 non-contextual columns in Set D, the leave-one-indentation-out reference statistics, the 10^{-9} denominator constant, the grouped folds, the remaining model settings and the prediction threshold were left unchanged. Second, the Random Forest C–D comparison was repeated with max_features fixed at 6 for both sets and at 7 for both sets. Runtime inspection of the fitted trees confirmed the nominal max_features setting under each condition. Third, the 11 samples whose 64 binary targets were all positive were removed. This target-defined exclusion retained 139 samples and 8,896 curves. A new five-fold StratifiedGroupKFold split was generated once on the retained samples and applied identically to paired Random Forest Set C and Set D fits. This analysis was retrospective and was not proposed as a label-free deployment filter.

2.8. Reproducibility and scope

The evidence package records the hashes of the analysis inputs, feature definitions, software environment, model constructors, fold assignments, fold-level metrics and row-level out-of-fold probabilities and predictions. The documented run used Python 3.12.14, scikit-learn 1.8.0, NumPy 2.3.5 and pandas 2.2.3. The ten instrument-summary variables were checked against the released summary files. The remaining descriptors were reconstructed from the released curves or within-sample values and compared with the archived modelling table using $|\text{archived} - \text{reference}| \leq 10^{-8} + 10^{-8}|\text{reference}|$. Here, reference denotes either the released summary value or the independently recomputed value. This comparison establishes numerical agreement for the released data, but it does not establish that the

unavailable historical feature-extraction code was identical or that it would behave identically in unobserved boundary cases. The source curves, instrument summaries and revised annotations are archived in the Materials Data Facility (Henriksen et al., 2025). The analysis-derived feature table, fold assignments and row-level predictions have been retained in the project evidence package, but have not been deposited in a public repository.

Before the post-hoc controls were interpreted, the six baseline C–D model configurations were refitted on the archived grouped folds and compared with the saved verification-run outputs (model_verification.json and model_oof.json). Their held-out sample lists matched the archive, their hard predictions had zero mismatches, the largest absolute probability difference was 2.22×10^{-16}, and the largest fold-metric difference was zero. The saved robustness outputs were subsequently re-aggregated from the row-level predictions by a separate verification script. These checks demonstrate internal computational reproducibility of the documented pipeline; they are not an external replication of the scientific findings.

The robustness analyses answer deliberately narrow questions. Clipping at the two specified thresholds does not identify a uniquely correct denominator guard or a unit-aware alternative to the 10^{-9} constant. Holding Random Forest max_features at 6 or 7 controls the candidate-feature count but not every change in representation or feature-sampling probability produced by adding 20 predictors. The exclusion analysis is defined by expert targets and contains no test of entirely normal samples. More broadly, the study remains confined to the released NiFe dataset and its contextual expert annotations. No external material system, laboratory, instrument configuration or independently labelled cohort was evaluated.

3. RESULTS AND DISCUSSION

3.1. Feature representation and classification performance

Among the evaluated configurations, the largest differences in mean balanced accuracy arose across feature sets rather than across classifiers within a set. Across 9,600 curves from 150 physical samples, Set A, which contained ten instrument-reported summaries, produced mean balanced accuracy values between 0.7499 and 0.7718. With the 33 curve-derived descriptors in Set B, the range rose to 0.9262–0.9281 (Table 1). These results indicate that the derived descriptors carried information associated with the expert anomaly labels that the instrument summaries did not capture as effectively. They do not identify a physical failure mechanism, and Sets A and B differ in both feature type and feature count. The finding is qualitatively consistent with the value of curve-derived features reported for a different nanoindentation classification problem by Trost et al. (2025), but the different materials, targets and validation designs preclude a direct comparison of scores.

Table 1. ***Classification performance under five-fold sample-grouped validation***

Model	Feature set	Predictors	Balanced accuracy	Anomalous-class F1
LR	A	10	0.7499 ± 0.0190	0.6761 ± 0.0280
LR	B	33	0.9281 ± 0.0105	0.9107 ± 0.0087
LR	C	43	0.9276 ± 0.0098	0.9095 ± 0.0075
LR	D	63	0.9328 ± 0.0098	0.9165 ± 0.0082
RF	A	10	0.7674 ± 0.0109	0.6987 ± 0.0170
RF	B	33	0.9268 ± 0.0168	0.9133 ± 0.0191
RF	C	43	0.9278 ± 0.0145	0.9140 ± 0.0164
RF	D	63	0.9356 ± 0.0127	0.9245 ± 0.0125
HGB	A	10	0.7718 ± 0.0103	0.7054 ± 0.0139
HGB	B	33	0.9262 ± 0.0194	0.9099 ± 0.0213
HGB	C	43	0.9245 ± 0.0229	0.9070 ± 0.0271
HGB	D	63	0.9326 ± 0.0175	0.9193 ± 0.0189

Note. Values are unweighted means ± sample standard deviations across five held-out folds. LR = logistic regression; RF = Random Forest; HGB = histogram gradient boosting. A contains instrument-reported summaries; B contains descriptors derived from individual load, depth and time records; C combines A and B; D adds 20 within-sample contextual descriptors to C.

Adding Set A to Set B did not produce a consistent improvement. Relative to B, Set C gave a small increase for Random Forest but small decreases for logistic regression and histogram gradient boosting. More predictors were therefore not automatically beneficial under the documented settings. The controlled context comparison is C versus D.

Adding the 20 contextual descriptors to Set C increased mean balanced accuracy and anomalous-class F1 for all three classifiers (Table 2). The balanced-accuracy increments were 0.005177 for logistic regression, 0.007770 for Random Forest and 0.008047 for histogram gradient boosting. For Random Forest, these mean gains corresponded to 0.777 percentage points in balanced accuracy and 1.051 percentage points in anomalous-class F1. Balanced accuracy increased in five of five folds for Random Forest and histogram gradient boosting and in four of five folds for logistic regression. F1 increased in all five folds for every model. The absolute changes were modest, and the fold signs are descriptive rather than evidence from five independent replications. The reported standard deviations are not confidence intervals, and overlap among the training sets limits formal inference from the folds (Bengio & Grandvalet, 2004).

Table 2 ***Paired changes after adding within-sample context***

Model	Mean change in BA	BA-positive folds	Mean change in F1	F1-positive folds
LR	+0.005177	4/5	+0.006971	5/5
RF	+0.007770	5/5	+0.010511	5/5
HGB	+0.008047	5/5	+0.012308	5/5

Note. Changes are Set D minus Set C and were calculated from unrounded scores on the same grouped folds. No formal significance test was performed.

Among the 12 primary model-feature configurations, RF-D had the highest mean balanced accuracy (0.9356) and F1 (0.9245). The ranking was not uniform across metrics: LR-D had higher anomalous-class recall than RF-D (0.9013 versus 0.8903), whereas RF-D had higher precision (0.9623 versus 0.9328). Selection for a practical workflow would therefore depend on the relative cost of a missed anomaly and an additional expert review, neither of which was measured here.

3.2. Validation design and target-defined sample exclusion

For RF-C, random indentation-level folds yielded balanced accuracy of 0.9375 ± 0.0073 and anomalous-class F1 of 0.9278 ± 0.0084; grouped folds yielded 0.9278 ± 0.0145 and 0.9140 ± 0.0164, respectively. The balanced-accuracy means differed by 0.009677 (approximately 0.968 percentage points). Every random fold included curves from all 150 samples in both training and testing, whereas grouped folds held out complete samples. The former evaluates additional curves from represented samples; the latter evaluates unseen physical samples within this dataset (Roberts et al., 2017). Because grouping also changes split composition, the score gap is not a causal estimate of a particular leakage mechanism.

Table 3 ***Random and grouped validation and the target-defined exclusion subset***

Table 3, panel A

Analysis	Model and set	Samples	Curves
Random indentation-level split	RF-C	150	9,600
Sample-grouped split	RF-C	150	9,600
Exclusion subset	RF-C	139	8,896

Analysis	Model and set	Samples	Curves
Exclusion subset	RF-D	139	8,896

Table 3, panel B

Analysis	Model and set	Balanced accuracy	Anomalous-class F1
Random indentation-level split	RF-C	0.9375 ± 0.0073	0.9278 ± 0.0084
Sample-grouped split	RF-C	0.9278 ± 0.0145	0.9140 ± 0.0164
Exclusion subset	RF-C	0.929893 ± 0.015751	0.914564 ± 0.014534
Exclusion subset	RF-D	0.935234 ± 0.015760	0.923601 ± 0.016331

Note. The random and grouped full-data rows use different split structures. The exclusion rows use the same newly generated grouped folds for C and D. Values are not equivalence estimates across populations.

Removing the 11 samples with 64 positive targets retained 139 samples, 8,896 curves, 2,705 anomalous curves and 6,191 normal curves. On the same regenerated grouped folds, RF-D exceeded RF-C by 0.005341 in mean balanced accuracy and 0.009037 in mean F1; both differences were positive in all five folds. The balanced-accuracy increment was smaller than the full-data RF increment of 0.007770. Thus, the direction persisted but its magnitude changed. Because expert targets defined the exclusion, this is a retrospective sensitivity analysis, not a pre-labelling deployment rule. Similar mean scores in the full and reduced data do not constitute an equivalence test.

3.3. Post-hoc robustness controls

Zero leave-one-indentation-out MAD values produced extreme contextual descriptors, with a largest absolute value of 2.850804×10^{9}. Clipping at ±100 changed 292 cells in 142 curves across 24 samples; clipping at ±10 changed 5,112 cells in 2,334 curves across all 150 samples. Mean Set D minus Set C balanced accuracy and F1 stayed positive for all three classifiers under both thresholds (Table 4), but the increments varied. Logistic regression's balanced-accuracy increment fell from 0.005177 without clipping to 0.002932 at ±10; Random Forest's was 0.010497 at ±100 and 0.006825 at ±10. HGB at ±10 had a positive mean increment, although balanced accuracy increased in four rather than five folds. The checks support the direction of the mean result at these thresholds, not an invariant magnitude or fold pattern.

Table 4*Context gain under the two clipping thresholds*

Table 4, panel A

Model	D condition	Balanced accuracy	Anomalous-class F1
LR	Unclipped	0.932764	0.916463
LR	Clip 100	0.932214	0.915621
LR	Clip 10	0.930520	0.913455
RF	Unclipped	0.935571	0.924534
RF	Clip 100	0.938298	0.927540
RF	Clip 10	0.934626	0.923413
HGB	Unclipped	0.932572	0.919305
HGB	Clip 100	0.932572	0.919305

Model	D condition	Balanced accuracy	Anomalous-class F1
HGB	Clip 10	0.933163	0.920721

Table 4, panel B

Model	D condition	Change in BA vs C	Change in F1 vs C	BA/F1-positive folds
LR	Unclipped	+0.005177	+0.006971	4/5 / 5/5
LR	Clip 100	+0.004627	+0.006129	4/5 / 5/5
LR	Clip 10	+0.002932	+0.003963	4/5 / 4/5
RF	Unclipped	+0.007770	+0.010511	5/5 / 5/5
RF	Clip 100	+0.010497	+0.013517	5/5 / 5/5
RF	Clip 10	+0.006825	+0.009390	5/5 / 5/5
HGB	Unclipped	+0.008047	+0.012308	5/5 / 5/5
HGB	Clip 100	+0.008047	+0.012308	5/5 / 5/5
HGB	Clip 10	+0.008638	+0.013725	4/5 / 5/5

Note. Only the 20 contextual columns were clipped. The feature base in C, reference construction, denominator constant, folds, remaining model settings and classification decision threshold were unchanged.

The square-root max_features rule gave nominal candidate counts of six for Set C and seven for Set D. The C–D comparison was therefore repeated with the candidate count fixed at six and at seven for both sets (Table 5). The fold-level balanced-accuracy differences were positive in all five folds under both controls, with mean increments of 0.007538 for six candidates and 0.008919 for seven. The corresponding F1 increments were 0.010234 and 0.011568. The persistent positive differences indicate that the nominal one-feature difference in candidate count does not by itself explain the gain. They do not isolate context from every consequence of adding 20 predictors, because the representation and the probabilities with which individual predictors are sampled still change.

Table 5 ***Random Forest C–D comparison with a fixed candidate-feature count***

Table 5, panel A

Condition	Nominal C / D candidate count	C balanced accuracy	D balanced accuracy
Square-root rule	6 / 7	0.927801	0.935571
Fixed 6	6 / 6	0.927801	0.935340
Fixed 7	7 / 7	0.926652	0.935571

Table 5, panel B

Condition	Nominal C / D candidate count	Change in BA	Change in F1	BA/F1-positive folds
Square-root rule	6 / 7	+0.007770	+0.010511	5/5 / 5/5
Fixed 6	6 / 6	+0.007538	+0.010234	5/5 / 5/5
Fixed 7	7 / 7	+0.008919	+0.011568	5/5 / 5/5

3.4. Detection across annotation categories

The grouped RF-D predictions did not perform uniformly across the seven annotation subsets (Table 6). RF-D predicted the anomalous class for 1,333 of 1,348 curves carrying a force-offset annotation and 952 of 989 carrying an unusual-unloading-curvature annotation. At the other end of the range, only 85 of 139 displacement-offset curves and 74 of 227 unusual-loading-curvature curves received an anomalous prediction. The latter corresponds to recall of 0.3260, despite the much stronger aggregate F1. Aggregate performance therefore should not be read as uniformly high detection across the annotation taxonomy.

Table 6 ***RF-D detection among curves carrying each anomaly annotation***

Annotation	Labelled curves	Represented samples	Detected curves	Recall
Force offset	1,348	132	1,333	0.9889
Unusual unloading curvature	989	140	952	0.9626
Fully anomalous sample	704	11	632	0.8977
Tip displacement decreases at holding	223	111	186	0.8341
Too deep	84	36	69	0.8214
Displacement offset	139	52	85	0.6115
Unusual loading curvature	227	69	74	0.3260

Note. Detected curves were assigned the anomalous binary class by their held-out RF-D model. Recall was calculated from pooled out-of-fold predictions within each annotated subset. Annotations can overlap, so the rows are not mutually exclusive or independent classes.

These values quantify binary detection among curves that carry an annotation; they do not show that the model recognized the annotation itself. A curve with several annotations may have received an anomalous prediction because of another irregularity. The 704 curves in the fully anomalous category are clustered within 11 physical samples, which limits any interpretation that treats them as 704 independent examples. The present analysis does not determine why unusual loading curvature was frequently missed. Resolving that question would require targeted inspection of the missed curves and, ideally, annotation evidence independent of the current feature and sample context.

3.5. Interpretation and scope

The contextual descriptors place each indentation relative to the other 63 measurements from its physical sample. This is relevant to the prediction target because the source expert viewed all 64 curves together, and feature-derived consistency checks then selected curves for expert re-review (Zakariya et al., 2026). The revised target may therefore reflect curve patterns emphasized during that review. The size of any such contribution to the model comparison cannot be isolated here; this limit of target construction differs from physical-sample overlap between training and test folds. The contribution tested here is narrower than the introduction of sample context itself: it is the addition of a specified, label-free within-sample reference representation to a fixed individual-curve feature base, evaluated with complete physical samples held out. The resulting gain measures closer agreement with contextual expert labels. It does not independently verify the physical origin of the labelled irregularities.

The robustness controls reduce three specific concerns without removing all uncertainty. Mean C–D differences remained positive for all three classifiers under both clipping thresholds; the Random Forest difference also remained positive when candidate-feature counts were equalized and when the 11 fully anomalous samples were removed. At the same time, the clipping results changed the magnitude of the gain, the fixed-count comparison did not hold the full representation constant, and the exclusion subset was defined using the target. These findings strengthen the internal case that the result is not explained solely by the tested extreme values, the nominal 6-versus-7 Random Forest candidate count or the fully anomalous samples. They do not convert the comparison into a causal estimate of a pure context mechanism.

The deployment setting is also constrained. Context for a new curve cannot be computed until the other curves from the same sample are available, so the approach is suitable for post-acquisition batch review rather than isolated real-time prediction. The reference distribution is a mixture of measurements and is not a known-normal control. Under the binary target used here, every sample contains at least eight positive curves, and 11 samples contain 64; consequently, performance on entirely normal samples or samples with very low within-sample anomaly prevalence remains unknown. Grouping prevents curves from the same physical sample from appearing in both training and test sets, but it does not establish independence across fabrication conditions, instruments or laboratories.

Finally, all model development and evaluation reported here use one released NiFe dataset. Fixed settings in the documented run do not prove that all earlier representation choices were made independently of observed performance, and such choices can influence estimated generalization (Cawley & Talbot, 2010). Transfer to another material system or acquisition workflow requires external data and independently generated labels. Practical deployment would also require decision thresholds selected for deployment, an explicit account of the costs of false negatives and additional reviews, and direct measurement of whether the system reduces expert workload. The present evidence supports further evaluation of within-sample context for batch screening; it does not support replacement of expert review.

4. CONCLUSION AND RECOMMENDATIONS

In this secondary analysis, the curve-derived descriptors in Set B predicted the revised expert anomaly labels more accurately than the instrument-reported summaries in Set A under sample-grouped validation. Adding 20 within-sample descriptors to the same 43 individual-curve predictors produced smaller positive mean gains in all three model families. Random Forest with Set D achieved balanced accuracy of 0.9356 ± 0.0127 and anomalous-class F1 of 0.9245 ± 0.0125. Relative to Set C, the corresponding increases were 0.007770 and 0.010511, with positive differences in all five grouped folds for both measures. These fold results are descriptive; no formal significance test was performed.

Clipping the contextual descriptors at either tested threshold left mean Set D minus Set C differences in balanced accuracy and F1 positive for all three classifiers, although their magnitudes changed. In Random Forest, the mean gains also remained positive when the nominal max_features setting was equal for Sets C and D, and when the 11 samples with 64 positive targets were excluded before both configurations were refitted. At the ±10 clipping threshold, histogram gradient boosting had a positive mean balanced-accuracy difference but a positive difference in only four of five folds. These checks address specific sensitivities; they do not separate the information in context from every other consequence of expanding the feature set.

The target is an expert judgement formed with access to all 64 curves from a sample, so closer agreement with that target does not independently establish the physical origin of a labelled irregularity. The contextual features require the other curves before prediction and therefore suit post-acquisition batch review. Evaluation on other materials, instruments, laboratories, entirely normal samples, and samples with low within-sample anomaly prevalence remains open. Further work should test independently generated expert labels in such settings, inspect the missed unusual-loading-curvature cases, and measure whether alternative decision thresholds reduce expert-review workload without an unacceptable increase in missed anomalies. The approach remains a candidate aid to expert screening, not a validated replacement for it.

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DESIGN AND DEVELOPMENT OF NEXT-GENERATION MODULAR STORAGE SYSTEMS

YENİ NESİL MODÜLER DEPOLAMA SİSTEMLERİNİN TASARIMI VE GELİŞTİRİLMESİ

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ÖZET

Günümüzde depolama mobilyalarının farklı kullanım alanları ve kullanıcı gereksinimlerine cevap verebilmesi, ürünlerin yalnızca belirli ölçü ve fonksiyonlara göre geliştirilmesi yerine farklı kullanım senaryolarına uyarlanabilen tasarım yaklaşımlarını gerekli hale getirmektedir. Farklı ölçü ve fonksiyonlar için ayrı ürünlerin tasarlanması; parça çeşitliliğinin artması, üretim süreçlerinin karmaşıklaşması, stok yönetiminin zorlaşması ve montaj süreçlerinin uzaması gibi sorunları beraberinde getirebilmektedir. Bu çalışmada, farklı kullanım ihtiyaçlarına uyarlanabilen, modüler yapıya sahip, yapısal dayanımı ve malzeme kullanımı dikkate alınarak kurgulanmış ve seri üretime uygun bir depolama dolap sisteminin tasarım ve geliştirme yaklaşımı ele alınmıştır.

Geliştirilen sistem, temel taşıyıcı elemanların ortak kullanımı prensibine dayandırılmış; farklı genişlik ve kapasitedeki ürünlerin mümkün olduğunca aynı temel komponentlerin farklı kombinasyonlarıyla oluşturulması amaçlanmıştır. Tasarım sürecinde modüler yapı, ortak komponent kullanımı, parça sayısının azaltılması, yapısal rijitlik, yük aktarımının dengelenmesi, montaj kolaylığı, üretim süreçlerinin sadeleştirilmesi, malzeme kullanımının optimize edilmesi ve farklı ölçülere uyarlanabilirlik temel kriterler olarak değerlendirilmiştir. Dikey ve yatay taşıyıcı elemanların belirli bir geometrik düzen içerisinde bir araya getirilmesiyle tekil modülden çoklu ve genişletilebilir sistemlere uzanan ölçeklenebilir bir ürün mimarisi oluşturulması hedeflenmiştir.

Yapısal tasarımda taşıyıcı elemanların konumları, bağlantı noktaları ve yük aktarım yolları dikkate alınarak yükün sistem içerisinde dengeli dağıtılması ve yeterli yapısal dayanımın gereğinden fazla malzeme kullanımına gidilmeden sağlanması esas alınmıştır. Üretilebilirlik açısından ortak parça kullanımının artırılması, parça çeşitliliğinin azaltılması, tekrarlanabilir üretim geometrilerinin ve standart bağlantı elemanlarının kullanılması ile üretim ve montaj işlemlerinin sadeleştirilmesi hedeflenmiştir. Sonuç olarak çalışma; modülerlik, yapısal dayanım, üretilebilirlik ve kullanım esnekliğini ortak bir ürün mimarisi içerisinde bütünleştiren, farklı kullanım alanlarına uyarlanabilir ve seri üretime yönelik bir depolama dolap sistemi tasarım yaklaşımı ortaya koymaktadır.

Anahtar kelimeler: Modüler tasarım, depolama dolabı, yapısal optimizasyon, üretilebilirlik, ürün geliştirme, seri üretim, tasarım mühendisliği.

ABSTRACT

Today, the need for storage furniture to meet the requirements of different application areas and users has made it necessary to adopt design approaches that can be adapted to various usage scenarios rather than developing products solely according to specific dimensions and functions. Designing separate products for different dimensions and functions may lead to increased part variety, greater complexity in production processes, difficulties in inventory management, and longer assembly processes. This

study presents the design and development approach of a modular storage cabinet system that can be adapted to different usage requirements, considers structural strength and material utilization, and is suitable for mass production.

The developed system is based on the principle of using common load-bearing elements, with the aim of creating products of different widths and capacities through various combinations of the same basic components wherever possible. During the design process, modularity, common component utilization, reduction in the number of parts, structural rigidity, balanced load transfer, ease of assembly, simplification of production processes, optimization of material use, and adaptability to different dimensions were considered as the main design criteria. By arranging vertical and horizontal load-bearing elements within a defined geometric configuration, a scalable product architecture extending from a single module to multiple and expandable systems was established.

In the structural design, the positions of the load-bearing elements, connection points, and load transfer paths were considered to achieve a balanced distribution of loads throughout the system and to provide adequate structural strength without excessive material use. In terms of manufacturability, the design focused on increasing the use of common parts, reducing part variety, employing repeatable production geometries and standard connection elements, and simplifying production and assembly operations. As a result, this study presents a storage cabinet design approach that integrates modularity, structural strength, manufacturability, and flexibility within a common product architecture, offering adaptability to different application areas and suitability for mass production.

Keywords: Modular design, storage cabinet, structural optimization, manufacturability, product development, mass production, design engineering.

INTRODUCTION

Today, the diversification of user requirements, the need to adapt to different application areas, and expectations for efficiency in manufacturing processes have made it necessary to adopt more flexible design approaches rather than developing products based solely on a single usage scenario or fixed dimensions. Particularly for product groups with varying dimensional, capacity, and functional requirements, increasing product variety provides advantages in meeting user needs; however, it may also introduce additional complexity into manufacturing systems in terms of part variety, inventory management, assembly operations, and production planning. Studies investigating the effects of product variety on manufacturing performance have shown that complexity arising particularly from part and option variety can negatively affect production performance (MacDuffie et al., 1996; Fisher and Ittner, 1999). Therefore, achieving an appropriate balance between the flexibility provided by product variety and the complexity arising in manufacturing processes has become an important issue in product development.

In this context, modular design has emerged as an important product development approach that enables different user requirements to be addressed through a common product platform. Product architecture is generally defined as the structure that determines how the functions of a product are allocated to physical components and how these components interact with one another (Ulrich, 1995). In modular product architecture, specific functions or structural sections of a product are organized into defined modules, allowing different product configurations to be developed within the same basic system. Modularity has been reported to be directly associated with product change, product variety, component standardization, and product development management (Ulrich, 1995). Similarly, the use of standardized component interfaces can facilitate the flexible development of different products or product variants (Sanchez and Mahoney, 1996).

One of the main objectives of the modular product development approach is to create a greater number of product variants using a limited number of basic components wherever possible. Studies on modularity focus on developing product architectures based on common modules and defined standards rather than completely redesigning products independently from one another (Gershenson et al., 2004). Dahmus et al. (2001) stated that the use of common and interchangeable modules within a product family can enable different products to be developed within a shared architecture. Similarly, product family and product platform approaches are based on creating product variants that address different user requirements through the use of common components and subsystems within the same basic design infrastructure (Jiao et al., 2007). This approach is particularly important for the systematic development of product families in product groups with varying dimensional and capacity requirements.

The use of common components is one of the important manufacturing-related aspects of modular product architecture. Collier (1981) investigated the relationship between component commonality and manufacturing system performance and demonstrated that part standardization can influence manufacturing variables such as total cost, work-center load, and delivery performance. Fisher et al. (1999) stated that component sharing, which involves using the same component across different products, represents an approach for controlling part variety in manufacturing operations while maintaining product variety in the market. The use of common components may also contribute to manufacturing different products within the same production infrastructure, thereby facilitating the management of the relationship between product variety and manufacturing complexity (Kim and Chhajed, 2000; Desai et al., 2001). Nevertheless, component commonality should be evaluated by considering the requirements of the product family and the need for differentiation among individual products.

Increasing product variety can affect not only the design process but also manufacturing and assembly operations. Fisher and Ittner (1999) demonstrated that variability in product options can influence manufacturing labor, production-line downtime, rework, and inventory levels. Salvador et al. (2002) indicated that modular product architecture can serve as an important means of reducing the adverse effects of product variety on operational performance; however, they emphasized that the appropriate modularity approach should be evaluated together with manufacturing characteristics such as production volume and product variety. Therefore, modular design can be regarded not merely as a method for creating different product options, but as an integrated design approach for managing the complexity generated by product variety within manufacturing systems.

Considering product design together with manufacturing and assembly requirements is also important for improving manufacturability. The design-for-manufacture-and-assembly approach is based on fundamental principles such as reducing the number of parts, facilitating the manufacture and assembly of components, and simplifying manufacturing processes as much as possible during product development (Dewhurst and Boothroyd, 1987; Boothroyd et al., 2011). Systematic engineering design approaches also recommend considering criteria such as manufacturing, assembly, cost, and product family development during the early stages of the design process, in addition to the functional requirements of the product (Pahl et al., 2007). Design decisions should therefore not be considered independently of manufacturing; instead, product geometry, number of parts, connection methods, and manufacturing methods should be evaluated in an integrated manner (Ulrich and Eppinger, 2016).

In modular systems, satisfying structural requirements is as important as manufacturability. Transforming a product into a modular system directly affects the design of connections between modules, load-bearing elements, and load-transfer paths. Therefore, modularity should not be regarded simply as dividing a product into separate parts; rather, a product architecture should be established in which functions, geometry, component relationships, and interfaces are systematically defined (Ulrich, 1995; Gershenson et al., 2004). In the development of modular products, the combined consideration of functional structures and common components supports the creation of different product variants based on the same fundamental system (Dahmus et al., 2001). Furthermore, increasing the use of common components and organizing a product family around a defined platform can contribute to establishing a reusable infrastructure for product development and manufacturing processes (Simpson et al., 2006; Jiao et al., 2007).

From the perspective of storage furniture, different application areas involve varying requirements in terms of width, height, capacity, and layout. The variation in storage requirements across offices, healthcare facilities, educational environments, archive areas, commercial spaces, and industrial workplaces highlights the importance of developing systems that can be adapted to different conditions rather than relying solely on individual products with fixed dimensions. Developing an entirely different construction for each dimension and capacity may increase part variety, diversify manufacturing operations, and complicate inventory management. Considering the effects of product variety on operational performance reported in the literature (Fisher and Ittner, 1999; Salvador et al., 2002), as well as the potential contributions of common component utilization to manufacturing systems (Collier, 1981; Fisher et al., 1999), the application of modular product architecture to storage systems represents an appropriate design approach for addressing these requirements in an integrated manner.

Accordingly, the aim of this study is to design and develop a storage cabinet system that can be adapted to different usage requirements, has a modular structure, is based on the use of common components,

considers structural strength and material utilization together, and is suitable for mass production. In the developed system, products with different widths and capacities were intended to be created, as far as possible, through different combinations of the same basic load-bearing components. Throughout the design process, modular structure, common component utilization, reduction in the number of parts, structural rigidity, balanced load transfer, ease of assembly, simplification of manufacturing processes, optimization of material use, and adaptability to different dimensions were considered as the main design criteria. Thus, the study aimed to establish a product architecture extending from a single module to multiple and expandable systems, adaptable to different usage scenarios, and compatible with a mass-production approach.

METHOD

In this study, a systematic design approach was applied to develop a modular storage cabinet system that can be adapted to different usage requirements and is suitable for mass production. The design and development process was addressed in five main stages: conceptual design, identification of common components, structural evaluation, optimization of manufacturing and assembly processes, and visualization and validation.

Determination of Design Requirements and Conceptual Design

In the first stage of the study, the fundamental design criteria required to adapt the storage system to different application areas and user needs were identified. In this context, modularity, common component utilization, reduction in the number of parts, structural rigidity, balanced load transfer, ease of assembly, simplification of manufacturing processes, optimization of material use, and adaptability to different dimensions were considered as the main design criteria.

Based on these criteria, the conceptual design was developed around a single module representing the basic structural unit of the system. The design approach was based on combining individual modules in different configurations, thereby enabling storage systems of different widths and capacities to be created within the same fundamental product architecture.

Development of the Modular Product Architecture

In the modular system design, the basic load-bearing structure was formed by arranging vertical and horizontal elements within a defined geometric configuration. While the vertical elements constituted the main load-bearing structure of the system, the horizontal elements were utilized to form storage compartments and contribute to the structural rigidity of the system.

The product architecture was developed according to the following approach:

Single Module → Module Group → Expandable System

Thus, products with different dimensions and capacities were intended to be created by using a single basic module in different numbers and combinations. Rather than developing entirely new constructions for different product dimensions, this approach was based on using different combinations of the same basic components.

Identification of Common Components

In the next stage of the design process, the basic load-bearing elements that could be commonly used across different product configurations were identified. The common component approach aimed to enable the same parts to be used in different module combinations and to achieve product variety through a limited number of basic components wherever possible.

Accordingly, the basic load-bearing elements were retained while adapting the system to different widths and capacities, whereas product variants were created through different geometric combinations of these elements. In this way, the design aimed to reduce part variety, increase common component utilization, and enable different products to be developed within the same fundamental design infrastructure.

Evaluation of Structural Design and Load Transfer

In the structural design of the system, the positions of the load-bearing elements, connection points, and load transfer paths were taken into consideration. To enable the storage system to carry loads that may occur during use, the arrangement of vertical load-bearing elements within the system, the contribution

of horizontal elements to structural rigidity, the geometry of the connection points, and the transfer of loads in the vertical direction were evaluated as part of the design process.
By positioning the load-bearing elements within a defined geometric arrangement, a balanced distribution of loads throughout the system was targeted. At the same time, the design aimed to provide adequate structural strength while avoiding excessive material use, thereby maintaining a balance between structural strength and material utilization.

Evaluation in Terms of Manufacturability and Assembly

The suitability of the developed modular system for mass production was considered one of the main criteria of the design process. In this context, increasing the use of common parts, reducing part variety, utilizing repeatable manufacturing geometries, employing standard connection elements, and simplifying assembly operations were targeted.
Through a product architecture based on the use of the same basic components in different product configurations, products of different dimensions were intended to be manufactured using a common production approach. In this way, the design aimed to prevent unnecessary diversification of manufacturing processes while increasing product variety and to enable production and assembly operations to be carried out in a more standardized manner.

Visualization and Design Validation

In the final stage of the design process, the developed modular product architecture was evaluated through three-dimensional visualizations. Product variants that could be created by combining the basic modules in different configurations were examined, and the adaptability of the system to different usage scenarios was visually evaluated.
At this stage, the applicability of the same module family to different product configurations was considered, while maintaining the fundamental product architecture during the transition from a single module to larger systems. Thus, the developed system was evaluated as a whole in terms of modularity, common component utilization, structural design, manufacturability, ease of assembly, and adaptability to different application areas.

RESEARCH FINDINGS AND DISCUSSION

The storage system developed in this study was evaluated in terms of modular product architecture, common component utilization, structural configuration, manufacturability, and adaptability to different usage requirements. As a result of the design process, a scalable product architecture ranging from a single module to multiple and expandable systems was established by using different combinations of basic load-bearing elements. Thus, products with different dimensions and capacities were intended to be created through various combinations of the same basic components without the need to develop entirely new constructions. This approach is consistent with studies indicating that modular product architecture enables different product variants to be developed within a common design infrastructure (Ulrich, 1995; Gershenson et al., 2004; Jiao et al., 2007).
In the developed system, vertical and horizontal load-bearing elements were arranged within a defined geometric configuration. The positions of the load-bearing elements, connection points, and load transfer paths were considered to achieve a balanced transfer of loads throughout the system. In addition, increasing common component utilization, reducing part variety, employing repeatable manufacturing geometries and standard connection elements, and simplifying production and assembly operations were targeted. The potential contributions of common component utilization to managing product variety and standardizing manufacturing processes have also been emphasized in the literature (Collier, 1981; Fisher et al., 1999; Salvador et al., 2002).
Evaluations based on three-dimensional visualizations showed that the same module family could be adapted to different product configurations. The modular bookcase/TV unit combination and executive desk application were considered examples of the implementation of this approach in different usage scenarios. Overall, the developed design approach integrates modularity, structural strength, manufacturability, and flexibility of use within a common product architecture. However, the structural performance of the system should be further validated through numerical analyses and experimental tests. Future studies may also include comparisons with existing systems in terms of production time, material consumption, number of parts, and cost.

CONCLUSION

In this study, a modular storage cabinet system adaptable to different usage requirements and suitable for mass production was developed. A scalable product architecture capable of accommodating various dimensions and capacities was established by using different combinations of common load-bearing elements. Throughout the design process, structural strength, balanced load transfer, manufacturability, ease of assembly, and material utilization were considered together. The proposed approach is considered to contribute to managing product variety through common components and enabling products for different application areas to be developed within the same design infrastructure. Future studies are planned to validate the structural performance of the system through numerical analyses and experimental methods.

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FROM CORRECT POSITIONING TO STANDARDIZED PRODUCTS IN ROBOTIC WELDING: THE ROLE OF WELDING FIXTURES IN THE PRODUCTION PROCESS

ROBOTİK KAYNAKTA DOĞRU KONUMDAN STANDART ÜRÜNE: KAYNAK FİKSTÜRLERİNİN ÜRETİM SÜRECİNDEKİ ROLÜ

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ÖZET
Üretim süreçlerinde kalite, süreklilik ve verimliliğin sağlanması, özellikle kaynaklı imalat uygulamalarında ürün standardizasyonu açısından büyük önem taşımaktadır. Robotik kaynak sistemleri; kaynak hızı, kaynak noktaları ve proses parametrelerinin önceden tanımlanabilmesi ve üretim çevrimleri boyunca tekrarlanabilmesi sayesinde kaynak prosesinin daha kontrollü yürütülmesine olanak sağlamaktadır. Bununla birlikte, robot sisteminin yüksek konumlandırma ve tekrarlama hassasiyeti, ürün geometrisinin ve ölçüsel özelliklerin her üretim çevriminde aynı şekilde korunması için tek başına yeterli değildir. Kaynak yapılacak parçaların doğru referans noktalarına göre konumlandırılması ve kaynak işlemi süresince sabit tutulması gerekmektedir. Bu çalışmada, robotik kaynak sistemlerinin üretimde sağladığı avantaj ve sınırlamalar ile kaynak fikstürlerinin ürün standardizasyonu, ölçüsel tekrarlanabilirlik ve proses verimliliği üzerindeki etkileri değerlendirilmiştir. Ayrıca Nitrocare Ar-Ge Merkezi bünyesinde tasarlanan ve üretilen kaynak fikstürlerinin geliştirme ve uygulama süreçleri incelenmiştir. Yapılan değerlendirmeler sonucunda, kaynak fikstürlerinin parçaların doğru referanslanması, konumlandırılması ve sabitlenmesi yoluyla ürün geometrisinin korunmasına ve üretim çevrimleri arasındaki ölçüsel tekrarlanabilirliğin sağlanmasına katkı sunduğu görülmüştür. Bununla birlikte fikstür tasarımında ürün geometrisi, kaynak sırası, robot hareketleri, operatör ergonomisi, üretim adedi ve kalite gereksinimlerinin birlikte değerlendirilmesi gerektiği belirlenmiştir. Sonuç olarak, robotik kaynak proseslerinde ürün standardizasyonunun yalnızca robot sisteminin hassasiyetine bağlı olmadığı; robot, ürün, kaynak parametreleri ve kaynak fikstürünün bütüncül olarak ele alınması gerektiği değerlendirilmiştir. Doğru tasarlanan ve doğrulanan kaynak fikstürlerinin robotik kaynak teknolojisinin sağladığı avantajların üretim sürecine etkin şekilde aktarılmasında önemli bir proses elemanı olduğu sonucuna varılmıştır.
Anahtar kelimeler: Robotik kaynak, kaynak fikstürü, ürün standardizasyonu, üretim tekrarlanabilirliği, proses verimliliği, kaynaklı imalat.

ABSTRACT
Ensuring quality, continuity, and efficiency in production processes is of great importance, particularly in terms of product standardization in welded manufacturing applications. Robotic welding systems enable the welding process to be carried out in a more controlled manner by allowing welding speed, welding points, and process parameters to be predefined and repeated throughout production cycles. However, the high positioning and repeatability accuracy of the robotic system alone is not sufficient to ensure that product geometry and dimensional characteristics are maintained consistently in each production cycle. The parts to be welded must be positioned according to the correct reference points and kept fixed throughout the welding process. In this study, the advantages and limitations of robotic welding systems in production, as well as the effects of welding fixtures on product standardization,

dimensional repeatability, and process efficiency, were evaluated. In addition, the development and application processes of welding fixtures designed and manufactured within the Nitrocare R&D Center were examined. As a result of the evaluations, it was observed that welding fixtures contribute to maintaining product geometry and ensuring dimensional repeatability between production cycles by enabling the correct referencing, positioning, and fixation of parts. Furthermore, it was determined that product geometry, welding sequence, robot movements, operator ergonomics, production volume, and quality requirements should be considered together in fixture design. Consequently, it was concluded that product standardization in robotic welding processes does not depend solely on the accuracy of the robotic system; rather, the robot, product, welding parameters, and welding fixture should be considered as an integrated system. Properly designed and validated welding fixtures were concluded to be an important process element in effectively transferring the advantages provided by robotic welding technology to the production process.

Keywords: Robotic welding, welding fixture, product standardization, production repeatability, process efficiency, welded manufacturing.

INTRODUCTION

Increasing competition in today's manufacturing industry is driving enterprises toward the goals of higher quality, shorter production times, lower costs, and repeatable production. Particularly in welded manufacturing processes, variations in product quality depending on operator experience, differences in production times, and geometric deviations that may occur during welding increase the importance of process control and automation. The use of industrial robots in welding applications provides significant advantages in terms of the programmability of welding movements, the controllability of process parameters, and the ability to perform the same production cycle with high repeatability (Pires et al., 2006; Ogbemhe & Mpofu, 2015). Developments in robotic arc welding technologies are not limited solely to the automation of robot movements; rather, they are progressing toward more controlled and flexible production systems through the integration of technologies such as sensor systems, image processing, adaptive control, and intelligent process control (Xu et al., 2015; Ogbemhe & Mpofu, 2015). In robotic welding systems, the positioning and repeatability accuracy of the robot manipulator is one of the fundamental parameters affecting process performance. In industrial robots, repeatability refers to the extent to which the robot can repeatedly reach a programmed position in successive cycles and is particularly important in processes such as welding that require precise trajectory tracking. However, the high positioning and repeatability accuracy of the robot alone does not guarantee the dimensional accuracy and geometric repeatability of the welded product. Variations in the geometry of the parts to be welded, manufacturing tolerances, thermal effects occurring during welding, and differences in the positioning of parts on the fixture may cause deviations between the welding path followed by the robot and the actual joint line (Pires et al., 2006; Xu et al., 2015).

Therefore, in robotic welding processes, it is of great importance that the parts are positioned according to the same reference points in each production cycle and maintained in the specified position throughout the welding process. Fixtures are important production equipment used to accurately position, support, and secure workpieces during manufacturing operations (Hargrove & Kusiak, 1994; Cecil, 2001). Fixture design is not limited solely to holding the workpiece but may also have a direct impact on product quality, production efficiency, process reliability, and manufacturing costs (Wang et al., 2010). Boyle et al. (2011) stated that fixtures play an important role in enabling products to be manufactured in accordance with design requirements by ensuring the accurate and secure positioning of workpieces. The primary purpose of welding fixtures is to ensure that the parts to be joined are correctly positioned relative to one another and to defined reference points, and to maintain this position until the welding process is completed. Correct positioning of the workpiece and appropriate restriction of its degrees of freedom are among the fundamental requirements for achieving dimensional accuracy in manufacturing processes (Hargrove & Kusiak, 1994; Wang et al., 2010). In this context, the appropriate determination of locators, support elements, and clamping points in fixture design is important in terms of workpiece stability, geometric accuracy, and the control of deformations that may occur during the process (Cecil, 2001; Boyle et al., 2011).

Particularly in the production of deformation-sensitive components, fixture layout and clamping conditions may have a determining effect on the final product geometry. Lu and Zhao (2015)

demonstrated that optimizing fixture layout in the fixturing of deformable sheet metal workpieces is important for the geometric accuracy of the part. This issue becomes even more important in welded manufacturing because localized heat input occurring during welding may generate residual stresses and dimensional deformations as a result of non-uniform heating and cooling. Therefore, it is not sufficient to consider a welding fixture merely as auxiliary equipment that holds parts in a specific position. Fixture design should be carried out by also considering the thermal and mechanical effects generated by the welding process.

In fixture design, the appropriate selection of clamping points and clamping forces is as important as the correct determination of reference points. Excessive or inappropriate clamping forces may cause undesirable deformation of the workpiece, whereas insufficient clamping may lead to movement of the part during the process and deterioration of positional accuracy. Therefore, it is recommended that fixture design be carried out by considering part geometry, manufacturing tolerances, and process requirements together (Wang et al., 2010; Boyle et al., 2011).

Another important consideration in fixture design for robotic welding applications is robot accessibility. Fixture elements should not restrict the movement range of the welding torch, should allow the robot to access the required welding regions at appropriate angles and distances, and should simultaneously secure the workpieces with sufficient rigidity. This transforms fixture design from merely a mechanical clamping problem into a multi-parameter design problem in which robot movements, welding path, product geometry, and production sequence must be considered together. Hajduk et al. (2009) demonstrated that a modular approach to fixture design for robotic spot-welding applications is important in terms of adapting to different production requirements.

Increasing product variety and variability in production volumes also create new requirements for fixture design. Although conventional product-specific fixtures can provide high accuracy and repeatability, they may have disadvantages such as design and manufacturing costs, preparation time, the need for modifications following product revisions, and storage requirements (Boyle et al., 2011). Therefore, the development of flexible, modular, and reconfigurable fixture systems has become an important research area in the literature. Shirinzadeh (1993) stated that reconfigurable fixture modules can provide significant advantages in terms of adaptability to different production conditions. Similarly, studies on flexible fixture design indicate that the ability of production systems to adapt more rapidly to changing product geometries can contribute to manufacturing flexibility (Gothwal & Raj, 2017).

One of the fundamental issues in fixture design is maintaining product geometry throughout production cycles. Minor variations in fixture layout or inappropriate positioning and clamping points may alter the geometric position of the part and consequently cause product dimensions to fall outside tolerance limits. Therefore, fixture design should be considered not only in terms of securing the part but also in terms of ensuring the dimensional repeatability of the process (Wang et al., 2010; Lu & Zhao, 2015). Particularly in robotic welding applications, since the robot repeats the programmed welding path in the same manner, it is critically important that the workpiece be positioned according to the same coordinate system in every production cycle.

From the perspective of robotic welding systems, transferring the robot's high repeatability accuracy to the product is possible only when the parts are positioned in a repeatable manner compatible with the robot coordinate system. Therefore, the robotic welding system and the welding fixture should not be considered as two independent production elements. The welding fixture is one of the complementary elements of the process that enables the robot's programmed welding path to be applied at the correct position on the actual workpiece. Although sensor and adaptive control technologies in robotic welding systems can compensate for certain variations in the part and welding line, the accurate and repeatable determination of the initial position of the part remains important for process stability (Ogbemhe & Mpofu, 2015; Xu et al., 2015).

Nevertheless, the use of welding fixtures also involves certain technical and economic limitations. The initial design and manufacturing costs of product-specific fixtures, the need for revisions following product changes, maintenance and periodic inspection requirements, and the storage space they require within the production area can be considered among these limitations. Therefore, fixture design should not be carried out solely from the perspective of securing the part; rather, product geometry, production volume, welding sequence, robot movements, operator ergonomics, maintenance requirements, and quality criteria should be considered together (Cecil, 2001; Boyle et al., 2011; Gothwal & Raj, 2017).

In this study, the advantages provided by robotic welding systems in welded manufacturing processes and the factors that should be considered in practice were addressed, and the role of welding fixtures in product standardization, dimensional repeatability, and process efficiency was investigated. In addition, welding fixtures designed and manufactured within the Nitrocare R&D Center for the robotic welding processes of different products were evaluated through practical application examples. Particular emphasis was placed on the effects of correct referencing, positioning, and securing of parts throughout the welding process on maintaining product geometry. Thus, the study aimed to evaluate the robotic welding system and welding fixture as complementary process components in achieving repeatable and standardized production.

METHOD

This study was conducted as an applied industrial study aimed at evaluating the role of welding fixtures used in robotic welding applications in product standardization, production repeatability, and process efficiency. Within the scope of the study, the robotic welding system used in the production processes of the Nitrocare R&D Center, operating under Gökler Group, and the welding fixtures designed and manufactured in-house for this system were examined.

The methodological approach of the study consisted of the following stages: evaluation of the product and welding process, determination of fixture requirements, identification of referencing and clamping points, design and manufacture of the fixture, positioning of the parts on the fixture, and evaluation of their applications in the robotic welding process.

Evaluation of the Product and Welding Process

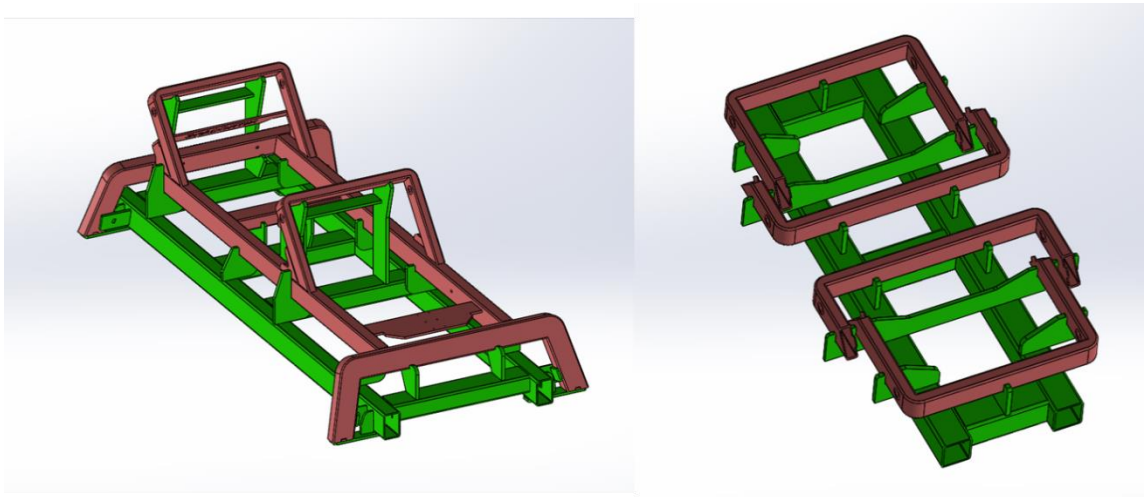
In the first stage, the geometric structure and welding regions of the products to be subjected to robotic welding were evaluated. In order to ensure that the parts were maintained in the correct position during the robotic welding process, product geometry, the relationships between the parts, the regions to be welded, and the robot's accessibility to these regions were taken into consideration. Based on these evaluations, a fixturing approach was determined to ensure that the parts could be positioned in the same location during each production cycle.

The fundamental approach in fixture design was to position the workpieces according to a repeatable reference system so that the robot could perform the programmed welding motion under the same conditions in each production cycle.

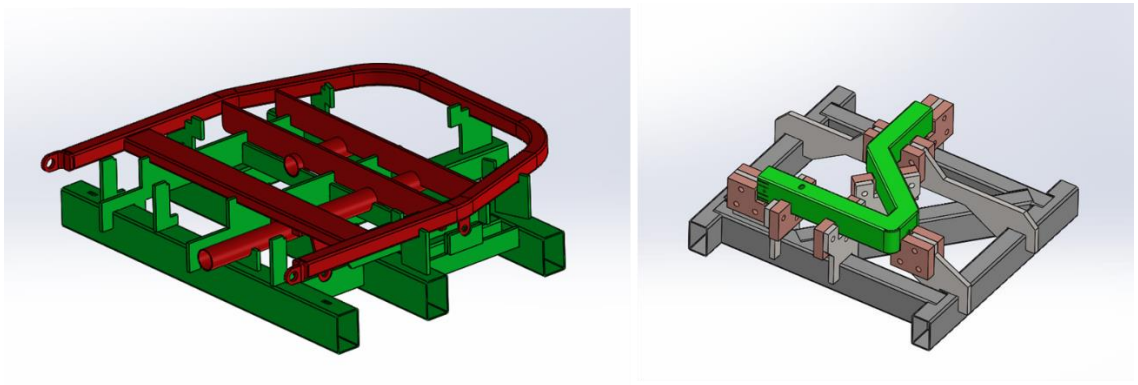
Determination of Referencing and Clamping Points

Product geometry was taken as the basis for determining the positions of the parts to be welded on the fixture. Appropriate reference points were determined to ensure that the parts could be positioned in the same location during each production cycle, and clamping regions were established to prevent movement of the parts during the welding process.

When determining the referencing and clamping points, maintaining the correct geometric relationship between the parts, ensuring accessibility to the welding regions, and preventing fixture elements from interfering with robot movements were taken into consideration. Thus, the fixture was intended to be used not merely as a device for securing the parts, but as a process element contributing to the preservation of product geometry throughout the welding process.



Ürün – Fikstür – Referanslama/Sabitleme



Ürün – Fikstür – Referanslama/Sabitleme

Design and Manufacturing of Welding Fixtures

The welding fixtures were designed in accordance with the determined product geometry, reference points, and clamping requirements. During the design process, the placement and removal of parts from the fixture, accessibility to the welding regions, the robot's range of motion, and the operating conditions within the production process were taken into consideration.

The designed fixtures were manufactured in-house and integrated into the robotic welding process. Following manufacturing, the product components were positioned on the fixtures, and the ability of the referencing and clamping elements to maintain the parts in the desired position was evaluated during application.

Robotic Welding Application

The parts positioned on the fixture were subjected to welding using the robotic welding system. In the robotic welding application, the same welding program was applied throughout the production cycles, enabled by the predefined welding speed, welding points, and process parameters.

At this stage, the primary function of the fixture was to ensure that the parts were positioned in accordance with the robot's programmed welding coordinates and that this position was maintained throughout the welding process. Thus, it was aimed to integrate the robot's repeatability accuracy with the positioning and clamping functions of the fixture within the production process.

Evaluation of Fixtures in Terms of the Production Process

The welding fixtures developed in-house were evaluated in terms of product standardization, dimensional repeatability, process efficiency, and quality consistency. In addition, the design and manufacturing requirements that should be considered in fixture applications were addressed.

The evaluation particularly focused on positioning the parts according to the same references in each production cycle, maintaining product geometry throughout the welding process, ensuring continued robot accessibility to the welding regions, and carrying out the production process in a repeatable manner. In addition, the need for product-specific fixture design, the determination of appropriate reference and clamping points, the control of manufacturing tolerances, the need for fixture modifications following product revisions, and the operating conditions of the fixtures within the production environment were also taken into consideration.

In accordance with this methodology, the interaction between the robotic welding system and the welding fixture within the production process was examined, and the contribution of fixture use to the standardization of the robotic welding process was evaluated through practical application examples.

RESEARCH FINDINGS AND DISCUSSION

Within the scope of the study, welding fixtures used in robotic welding processes and designed and manufactured in-house at the Nitrocare R&D Center were evaluated in terms of product standardization, dimensional repeatability, process efficiency, and quality consistency. The applications demonstrated that, in order to effectively transfer the high repeatability capability of the robotic welding system to the production process, it is important to position the parts according to the same reference points in each production cycle and to keep them fixed throughout the welding process. The robot's ability to repeat the same welding program with high accuracy alone is not sufficient to maintain product geometry and dimensional consistency when variations occur in the positioning of the parts. Therefore, the repeatability accuracy of the robot and the positioning and clamping functions of the fixture were considered complementary elements.

The welding fixtures examined were found to contribute to positioning the parts according to predefined references and maintaining their positions throughout the welding process. Thus, the combined application of a standardized welding program and standardized part positioning becomes possible in the robotic welding process, supporting the preservation of product geometry between production cycles. This assessment is consistent with studies in the literature emphasizing the importance of fixture design for product quality, manufacturing accuracy, and process efficiency (Hargrove & Kusiak, 1994; Wang et al., 2010; Boyle et al., 2011). Similarly, Lu and Zhao (2015) demonstrated that fixture layout has significant effects on the geometric accuracy of workpieces, particularly those susceptible to deformation.

The ability of fixtures to facilitate the positioning of parts according to defined reference points during production cycles also contributes to a more systematic and controlled production process. Rather than determining the position of the part based on operator judgment in each cycle, the use of predefined referencing and clamping elements supports the reduction of operator-related variability. From this perspective, welding fixtures should be regarded not merely as auxiliary equipment for securing parts but as production elements that support the standardization and quality consistency of the robotic welding process (Cecil, 2001; Ogbemhe & Mpofu, 2015).

However, product geometry, the determination of appropriate reference and clamping points, manufacturing tolerances, and robot accessibility should be considered together in fixture design. While fixture elements must provide sufficient clamping of the part, they should not restrict the movement of the robotic welding torch or its access to the welding regions. Furthermore, the design and manufacturing costs of product-specific fixtures, the need for modifications following product revisions, periodic inspection and maintenance requirements, and storage requirements should also be taken into consideration. Therefore, modular and reconfigurable fixture approaches may offer advantages in production systems characterized by high product variety (Hajduk et al., 2009; Gothwal & Raj, 2017).

Overall, the findings of this study indicate that product standardization and repeatability in robotic welding processes do not depend solely on the accuracy of the robotic system; rather, the robot, workpiece, welding parameters, and welding fixture should be evaluated through an integrated approach. Properly designed welding fixtures that are appropriately implemented within the production process were considered important complementary components of robotic welding systems in terms of accurate positioning and clamping of parts, preservation of product geometry, dimensional repeatability, and process efficiency.

CONCLUSION

In this study, the role of welding fixtures used in robotic welding systems in product standardization, dimensional repeatability, and process efficiency was evaluated. As a result of examining the application processes of welding fixtures designed and manufactured within the Nitrocare R&D Center, it was observed that the high positioning and repeatability accuracy of the robotic welding system alone is not sufficient to achieve standardized production; rather, it is important that the parts be positioned according to the correct references in each production cycle and maintained in a fixed position throughout the welding process.

Welding fixtures were considered an important component of the production process not only for the accurate positioning and clamping of parts but also for preserving product geometry, supporting dimensional consistency between production cycles, and reducing operator-related variability. Furthermore, it was concluded that product geometry, reference and clamping points, welding sequence, robot accessibility, operator ergonomics, production volume, and quality requirements should be considered together in fixture design.

In conclusion, in order to establish a repeatable and standardized production structure in robotic welding applications, the robot, workpiece, welding parameters, and welding fixture should be considered through an integrated approach. Properly designed welding fixtures that are appropriately implemented within the production process are expected to contribute to the more effective transfer of the advantages provided by robotic welding technology to production and to the establishment of a sustainable quality standard.

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EFFECT OF INCIDENT OPTICAL POWER DENSITY ON THE PHOTORESPONSE OF A DOPED GRAPHENE QUANTUM DOT-BASED HETEROJUNCTION

GELEN OPTİK GÜÇ YOĞUNLUĞUNUN KATKILI GRAFEN KUANTUM NOKTA TABANLI HETEROEKLEMİN FOTOCEVABI ÜZERİNDEKİ ETKİSİ

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Abstract
This work examines how incident optical power density governs the photoresponse characteristics of a doped graphene quantum dot-based heterojunction over the 20-100 mW/cm^2 range. Current-voltage measurements were performed over a bias range of -2.5 to +1.5 V under dark conditions and at five different illumination intensities. At -2.5 V, the dark current was approximately 9.48 µA, while illumination resulted in a pronounced enhancement of the device current. The power-dependent photodetection behavior was further evaluated through sensitivity, responsivity, external quantum efficiency (EQE), and specific detectivity (D*). As the incident power density increased from 20 to 100 mW/cm^2, the sensitivity increased from 9.91 to 29.34. In contrast, the responsivity exhibited an overall decrease from 0.598 to 0.354 A/W. A similar trend was observed for EQE and D*, which changed from 134.8% to 79.8% and from 3.04 × 10^{10} to 1.80 × 10^{10} Jones, respectively. The highest responsivity, EQE, and detectivity were therefore achieved at 20 mW/cm^2, whereas higher illumination levels produced greater sensitivity. The different intensity-dependent trends observed in these performance parameters suggest that increasing photon flux affects the balance among carrier generation, interfacial trapping, trap filling, and recombination processes. Overall, the results demonstrate that the photodetection characteristics of the heterojunction are strongly dependent on incident optical power density and provide insight into the underlying intensity-dependent carrier dynamics.
Keywords: Doped graphene quantum dots, heterojunction, incident optical power density, photodetector performance

Özet
Bu çalışmada, 20-100 mW/cm² aralığındaki ışık şiddetinin katkılı grafen kuantum nokta tabanlı bir heteroeklemin fotocevap özellikleri üzerindeki etkisi incelenmiştir. Akım-gerilim ölçümleri, -2,5 ile +1,5 V gerilim aralığında, karanlık koşullarda ve beş farklı ışık şiddeti altında gerçekleştirilmiştir. -2,5 V'ta karanlık akım yaklaşık 9,48 µA olarak belirlenirken, aydınlatma altında aygıt akımında belirgin bir artış gözlenmiştir. Optik güce bağlı fotodedeksiyon davranışı; duyarlılık, responsivite, dış kuantum verimi (EQE) ve özgül dedektivite (D*) parametreleri üzerinden ayrıca değerlendirilmiştir. Gelen optik güç yoğunluğu 20 mW/cm2'den 100 mW/cm^2'ye artırıldığında duyarlılık 9,91'den 29,34'e yükselmiştir. Buna karşılık responsivite genel olarak azalarak 0,598 A/W'den 0,354 A/W'ye düşmüştür. Benzer bir eğilim EQE ve D* için de gözlenmiş ve bu değerler sırasıyla %134,8'den %79,8'e ve 3,04 × 10^{10} Jones değerinden 1,80 × 10^{10} Jones değerine değişmiştir. En yüksek responsivite, EQE ve dedektivite değerleri 20 mW/cm^2'de elde edilirken, daha yüksek ışık şiddetlerinde daha yüksek duyarlılık gözlenmiştir. Bu performans parametrelerinde gözlenen ışık şiddetine bağlı farklı eğilimler, artan foton akısının taşıyıcı üretimi, arayüzey tuzaklanması, tuzak durumlarının dolması ve rekombinasyon süreçleri arasındaki dengeyi etkilediğine işaret etmektedir. Genel olarak sonuçlar, heteroeklemin fotodedeksiyon özelliklerinin gelen optik güç yoğunluğuna güçlü biçimde bağlı olduğunu göstermekte ve ışık şiddetine bağlı temel taşıyıcı dinamiklerinin anlaşılmasına katkı sağlamaktadır.
Anahtar kelimeler: Katkılı grafen kuantum noktaları, heteroeklem, ışık şiddeti, fotodedektör performansı

GİRİŞ

Kuantum noktaları, nanometre ölçeğinde yarı iletken parçacıklardır ve bu nedenle nanokristaller olarak da adlandırılırlar. Kuantum noktalarının (QD'ler) eksitonları üç boyutta sınırlandırıldığından, QD'ler benzersiz optik ve elektriksel özellikler sergilerler. QD'lerin en önemli özelliği kuantum sınırlama etkisidir. QD'lerin boyutları Bohr yarıçapından daha küçük hale geldikçe, sürekli enerji seviyeleri kuantize olmaya başlar. Bu ilkeye göre, enerji seviyesi değeri QD'lerin boyutuna göre ayarlanabilir. Kuantum noktalarının boyutunun küçültülmesi, enerji bant aralığının artmasına yol açar; dolayısıyla emisyon ve absorpsiyon tepe noktalarında maviye kayma meydana gelir. Bu durumda, sentez sırasında reaksiyon sıcaklığı, süresi, öncü madde, ligand vb. yoluyla kuantum noktalarının boyutlarının kontrol edilmesi suretiyle, belirli emisyon ve absorpsiyon özelliklerine sahip kuantum noktalarının tasarımı gerçekleştirilebilir.Kuantum noktalarının bu benzersiz özellikleri, optik ve elektronik cihazlardaki uygulamalar için büyük bir potansiyel sunmaktadır(Wang et al. 2023).

Grafen kuantum noktası (GQD), nanokarbon malzemeleri ailesinin en yeni üyesidir. Genellikle 10 nm'den küçük yanal boyutlara sahip, atomik incelikte bir grafitik düzleme (genellikle 1 veya 2 tabaka, <2 nm kalınlığında) sahip, sıfır boyutlu (0D) bir grafen malzemesidir. İki boyutlu (2D) muadili olan grafen tabakasıyla karşılaştırıldığında GQD; kuantum sınırlamasından kaynaklanan bant aralığı ayarlanması, mükemmel dağılabilirlik, daha bol aktif bölgeler (kenarlar, fonksiyonel gruplar, katkı atomları vb.) özelliklere sahip olmasıyla, daha verimli, hızlı, esnek ve gelişmiş performansa sahip elektronik cihazların geliştirilmesine katkıda bulunabilir(Yan et al. 2019).

Seryumoksit (CeO_2), 3,2–3,6 eV bant aralığına sahip bir lantanit üyesidir. Optoelektronik uygulamalar için olağanüstü özellikler sergileyerek model bir metal oksit olarak seçilmiştir(Zhang et al. 2025).

Nadir toprak oksidi CeO_2, güçlü UV emilimi, olağanüstü termal ve kimyasal kararlılık, yüksek elektrik iletkenliği ve düşük maliyet sunarak, kendi kendine çalışan (self-powered) UV fotodedektörleri (UVPD) için ideal bir aday haline gelmektedir. CeO_2 temel bir özelliği, seryum iyonlarının Ce^{+3} ve Ce^{+4} olmak üzere iki yükseltgenme basamağında bir arada bulunmasıdır; bu durum elektron transfer verimliliğini artırır ve UV bölgesindeki ışık emilimini güçlendirir. Ayrıca, CeO_2 yüksek konsantrasyonda içsel oksijen boşlukları (OV'ler) içerir; bu boşluklar, elektron verici olarak işlev görerek yük taşınımını iyileştirir ve taşıyıcı ömürlerini uzatır. Bu avantajlı özellikleri sayesinde CeO_2, son zamanlarda kendi gücünü üreten UVPD uygulamaları için yoğun ilgi görmektedir. Li ve ark. van der Waals heteroyapıları üretmek için hidrotermal aşağıdan yukarıya birleştirme yöntemini kullanmışlardır; bu yapılar, 1D CeO_2 ile 0D bizmut kuantum noktalarının entegre edilmesiyle oluşturulmuştur. Elde edilen yapı, 1,0 M KOH çözeltisinde kararlı bir fototepki sergilemiştir. Huang ve ark. piezoelektrik ve piezo-fototronik etkiler sergileyen polidopamin kaplı seryum oksit (CeO_2@PDA) nanopartikülleri ve poli(viniliden florür) (PVDF) nanofiber tekstiller hakkında bildirimde bulunmuştur. Bununla birlikte, bu kompozit bazlı PD, 10 mW cm^{-2} ışık yoğunluğu altında sadece $5{,}21 \times 10^5$ Jones'luk bir algılama hassasiyeti elde etmiştir ki bu değer nispeten düşüktür. Bu sınırlama, muhtemelen PVDF matrisinin düşük iletkenliğinden ve CeO_2@PDA nanopartiküllerinin homojen olmayan dağılımından kaynaklanmaktadır; her ikisi de verimli yük taşınımını engellemektedir(Huang et al. 2025).

Bu çalışmada, GQD'lerin optoelektronik performansını geliştirmek amacıyla CeO_2 nanopartikülleri ile oluşturulan CeO_2NP/PEI-N-GQD nanokompozitleri çevre dostu hidretermal işlemle sentezlendi. -2,5 ile +1,5 V gerilim aralığında, karanlık koşullarda ve beş farklı ışık şiddeti altında hassasiyet (S), foto-cevap (R), detektivite (D*) ve dış kuantum verimliliği (EQE) parametreleri incelenerek fotodetektör özellikleri incelenmiştir.

YÖNTEM

CeO_2NP/PEI-N-GQD nanokompozit yapının sentezlenmesinde İki adım var. İlk olarak PEI-N-GQD sentezi belirlenen miktarlardaki sitrik asit (CA) ve polietilenimin (PEI), deiyonize su içerisinde tamamen çözülmüştür. Homojen çözelti otoklava aktarılmış ve hidrotermal işleme tabi tutulmuştur. İkinci aşamada hazırlanan süspansiyona, önceden deiyonize suda çözülmüş $Ce(NO_3)_3 \cdot 6H_2OCe(NO_3)_3 \cdot 6H_2$ öncül çözeltisi ilave edilerek Hidrotermal işlem sonucunda CeO_2NP/PEI-N-GQD nanokompozitleri elde edilmiştir. Dedektör yapısı, ilk olarak, Altın omik kontak n tipi si levha üzerine fiziksel buhar biriktirme yoluyla biriktirildi. Daha sonra Sentezlenen CeO_2NPs/PEI N-GQDs çözeltileri, n tipi Si levha üzerine spin coating olarak kaplandı. Son olarak, metal bir gölge maskesi kullanılarak PVD yöntemiyle nanokompozit tabaka üzerine dairesel Altın kontaklar oluşturuldu. Uygulanan bu adımların ardından CeO_2NP/PEI-N-GQD heteroyapılı dedektör yapısı elde edilmiştir.

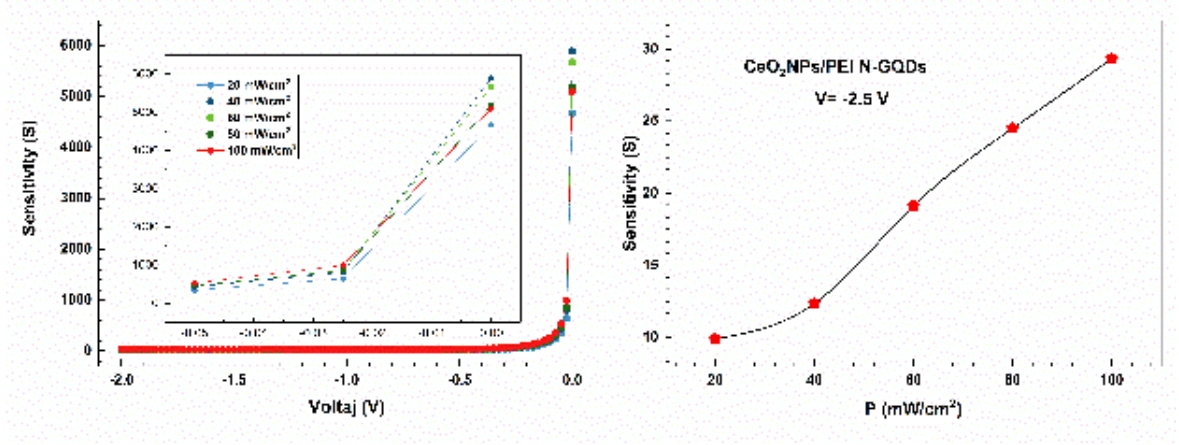
ARAŞTIRMA BULGULARI VE TARTIŞMA

Tablo1. de sentezlenen katkılı grafen kuantum nokta tabanlı bir heteroeklemin 20 ve 100 mW/cm² ışık şiddetlerindeki fotodedektör verileri incelenmiştir. Hibrit yapı, 20 mW/cm² optik güç yoğunluğunda daha yüksek kuantum verimi %134, responsivity 0.598A/W ve dedektivite 3,04 × 10^{10} Jones sergilerken; 100 mW/cm² yüksek güç yoğunluğunda taşıyıcı rekombinasyonu ve doyum etkileri nedeniyle bu parametrelerde düşüş, buna karşın toplam fotoakım artışına bağlı olarak hassasiyette 29.34 belirgin bir yükseliş göstermektedir.

Tablo 1. CeO_2NPs/PEI N-GQDs Heteroeklemin Fotodedektör Performansı

Işık Gücü	Sensitivity (S)	Responsivity (R) A/W	Dedektivity (D^*) Jones	EQE %
20 mW/cm^2	9.91	0,598 A/W	3,04 × 10^{10} Jones	%134,8
1000 mW/cm^2	29.34	0,354 A/W	1,80 × 10^{10}Jones	%79,8

CeO_2NPs/PEI N-GQDs heteroeklemin voltaja karşı hassasiyet (sensitivity) ve -2.5 V'da ışık gücüne bağlı sensitivity değişimi grafiği Şekil 1'de verilmiştir. Grafik incelendiğinde, hibrit yapının -2 V ila -0,5 V potansiyel aralığında neredeyse sabit kaldığı ve yalnızca ihmal edilebilir dalgalanmalar sergilediği anlaşılmaktadır. Ancak voltaj 0 V'a yaklaştıkça hassasiyette ani ve belirgin bir artış meydana gelmiştir. Bu hızlı yükseliş, hibrit yapının düşük bias altında fotodeteksiyon performansının önemli ölçüde iyileştiğini ve özellikle 0 V civarında yüksek hassasiyet sergilediğini göstermektedir. Optik güç yoğunluğu 20 mW/cm^2'den 100 mW/cm^{2}ye çıktıkça duyarlılık değeri yaklaşık 9.9'dan başlayarak yaklaşık 29.4'e kadar düzenli ve belirgin bir şekilde artmaktadır. Bu durum, artan foton akısının aktif alanda daha fazla elektron-deşik çifti (fototaşıyıcı) üretmesiyle ilişkilendirilebilir.

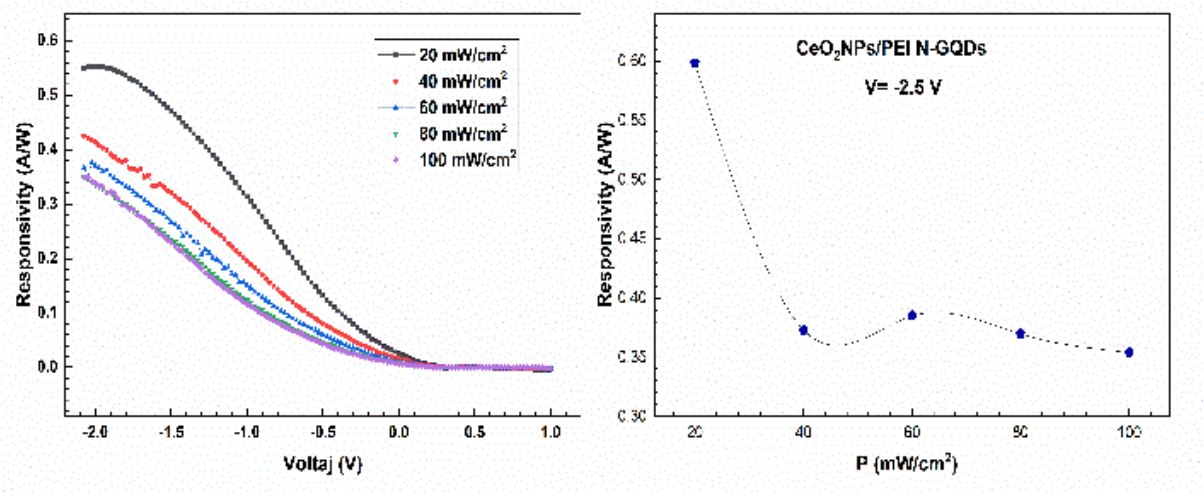


(a) (b)

Şekil 1. Ce katkılı PEI N-GQDs foto diyotların a) voltaja karşı hassasiyet grafiği b) ışık gücüne bağlı sensitivity değişimi grafiği

Şekil 2'de, farklı optik güç yoğunlukları 20 – 100 mW/cm^2 altında fotodedektörün Responsivity, uygulanan voltaja (-2.0V ile +1.0 V aralığı) bağlı değişimini göstermektedir. Ters besleme geriliminin 0 V'tan -2.0 V'a çıkarılmasıyla responsivitede keskin bir artış gözlenmiştir. Ters bias altında genişleyen tükenim bölgesi ve güçlenen dahili elektrik alan, fototaşıyıcıların sürüklenme hızını artırarak elektron-deşik çiftlerinin rekombinasyona uğramadan toplanmasını kolaylaştırmaktadır. İleri besleme bölgesinde V > 0.2 V ise arayüz bariyerinin zayıflaması nedeniyle foto-akım toplanması engellenmiş ve responsivite sıfıra yaklaşmıştır. Aygıtın responsivitesi, en düşük güç yoğunluğu olan 20 mW/cm^2'de maksimum yaklaşık olarak 0.60A/W değerine ulaşmış, artan ışık gücüyle birlikte azalarak 100 mW/cm^2'de yaklaşık 0.35 A/W seviyesine gerilemiştir. Responsivitenin artan güç yoğunluğu ile

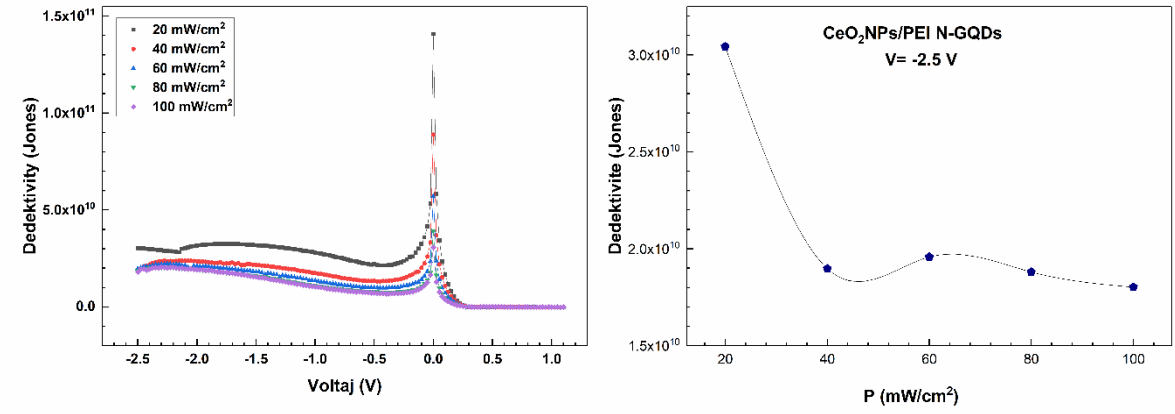
sergilediği bu ters orantılı davranış, fotodedektörlerde sıklıkla gözlenen foto-taşıyıcı tuzaklama ve rekombinasyon kinetiği ile açıklanmaktadır.



(a) **(b)**

Şekil 2. Ce katkılı PEI N-GQDs foto diyotların**.** (a) voltaja karşı foto-cevap grafiği, (b) ışık gücüne bağlı foto-cevap değişimi grafiği

Şekil 3'te D^* parametresinin, uygulanan gerilim ve farklı optik güç yoğunluklarına bağlı değişimi incelenmiştir. Grafiğin en dikkat çekici özelliği, uygulanan ışık gücü arttıkça algılama değerinde görülen sürekli ve güçlü artıştır. Elde edilen eğriler, sıfır gerilim 0V civarında dedektivitede keskin bir rezonans benzeri artış ortaya koymaktadır. En düşük optik güç yoğunluğunda maksimum tepe değerine ulaşmaktadır. Bu keskin pik, sıfır-bias bölgesinde termal ve tünelleme kaynaklı karanlık akımın minimuma inmesiyle gürültü seviyesinin dramatik biçimde bastırılmasından kaynaklanmaktadır. Bu sonuç, nanokompozit yapının harici bir güç beslemesine gereksinim duymaksızın yüksek hassasiyetli bir kendi kendine çalışan (self powered) fotodedektör olarak çalışabildiğini kanıtlamaktadır. Aygıtın dedektivitesi 20 mW/cm2 de en yüksek değeri olan yaklaşık 3.05 x1010Jones seviyesine ulaşmış, artan ışık şiddetiyle azalarak 100 mW/cm2'de 1.80x1010 Jones değerine gerilemiştir.

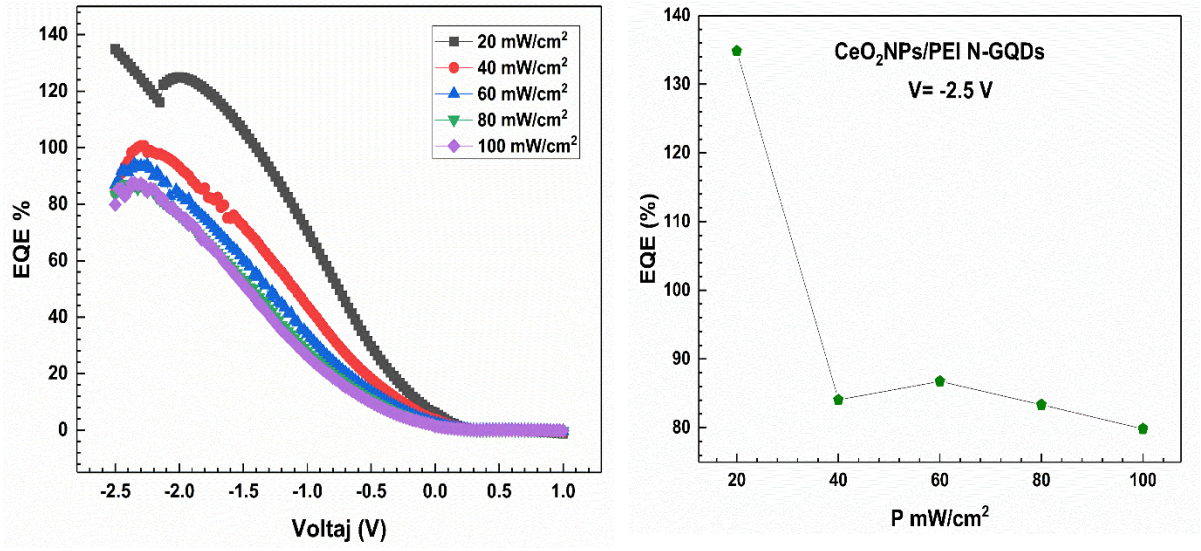


(a) (b)

Şekil 3. Ce katkılı PEI N-GQDs foto diyotların (a) voltaja karşı dedektivite grafiği (b) güce karşı dedektivite grafiği

Şekil 4'te, farklı optik güç yoğunlukları altında aygıtın Harici Kuantum Veriminin uygulanan gerilime bağlı değişimini göstermektedir. Ters besleme geriliminin artmasıyla birlikte güçlü elektrik alanın taşıyıcı ayrışmasını kolaylaştırması sonucunda EQE değerlerinde dikkate değer bir yükseliş kaydedilmiştir. En düşük güç yoğunluğunda 20 mW/cm^2'de EQE değeri yaklaşık %135 gibi yüksek bir

seviyeye ulaşarak teorik birlik sınırını aşmıştır. Bu durum, seryum katkısı kaynaklı lokalize kusur seviyelerinin ve oksijen boşluklarının fototaşıyıcı ömrünü uzatmasıyla devreye giren fotoiletken kazanç mekanizması ile açıklanmaktadır.



(a) (b)

Şekil 4. Ce katkılı PEI N-GQDs foto diyotların (a) voltaja karşı EQE grafiği (b) güce karşı EQE grafiği

SONUÇ

Bu çalışmada, CeO_2 katkılı ve PEI ile işlevselleştirilmiş azot katkılı grafen kuantum noktaları sentezlenmiş ve Au/CeO_2NPs/PEI-N-GQDs/n-Si/Au heteroeklem aygıtlarında bir arayüz katmanı olarak kullanılmıştır.

Elde edilen nanokompozitin optoelektronik performansı değerlendirilmiştir. Schotky fotodiyotun farklı ışık yoğunlukları için akım-voltaj ölçümleri yapıldı ve diyot için temel fotodiyot parametreleri sensitivity, responsivity, dedektivity ve EQE değerleri belirlendi.

Üretilen aygıtlar belirgin bir doğrultma davranışı ve aydınlatma altında kayda değer bir foto-yanıt sergilemiş; böylece CeO_2 modifiyeli PEI N-GQDs nanokompozitlerinin, çözelti tabanlı yöntemlerle üretilen silisyum esaslı fotodetektör uygulamaları için potansiyelini ortaya koymuştur. İncelenen fotodiyot parametreleri literatürle karşılaştırıldığında, üretilen hibrit yapının bir fotodiyot olarak iyi performans gösterdiği ve optoelektronik teknolojilerde kullanım için geliştirilebileceği tespit edildi.

Gelecek araştırmalarda; arayüz mühendisliği, farklı katkı konsantrasyonları ve uygun bant hizalanmasının optimize edilmesi yoluyla fotodedeksiyon özelliklerinin geliştirilmesi hedeflenebilir.

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BİZMUT KATKILI GRAFEN KUANTUM NOKTA TABANLI BİR HETEROEKLEMİN 24 AY SONRAKİ FOTODEDEKSİYON PERFORMANSI

PHOTODETECTION PERFORMANCE OF A BISMUTH-DOPED GRAPHENE QUANTUM DOT-BASED HETEROJUNCTION AFTER 24 MONTHS

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ÖZET

Grafen kuantum noktaları (GQD'ler), ayarlanabilir elektronik ve optik özellikleri, yüksek yüzey alanları ve çevre dostu üretime uygunlukları sayesinde optoelektronik uygulamalar açısından önemli bir potansiyele sahiptir. GQD'lerin heteroatomlarla katkılanması, elektronik yapı ve yük taşıma özelliklerinin kontrol edilmesine imkân sağlayarak fotodedektör performansının iyileştirilmesi için etkili bir yaklaşım sunmaktadır. Özellikle bizmut katkısı, GQD tabanlı yapıların elektronik özelliklerinin modüle edilmesi ve fotoindüklenmiş yük taşınımının geliştirilmesi açısından dikkat çekmektedir. Bu çalışmada, bizmut katkılı GQD tabanlı bir heteroeklemin 24 aylık bekletme sonrasındaki fotodedeksiyon performansı incelenmiş ve elde edilen sonuçlar başlangıç fotodedeksiyon karakteristikleriyle karşılaştırılmıştır. Başlangıç ölçümleri 96 mW/cm², 24 ay sonraki ölçümler ise 100 mW/cm² ışık yoğunluğu altında gerçekleştirilmiştir. Fotodedektör performansı; responsivite (R), hassasiyet (S), dış kuantum verimi (EQE) ve spesifik dedektivite (D*) parametreleri kullanılarak değerlendirilmiştir. Başlangıç ölçümlerinde, ışık yoğunluğunun artmasıyla ters akımın sistematik olarak arttığı ve aygıtın belirgin bir fotocevap sergilediği gözlenmiştir. 96 mW/cm² ışık yoğunluğunda ve −4 V'ta R = 0,12 A/W, S = 9 × 10², EQE = %27 ve D* = 5,6 × 10¹⁰ Jones değerleri elde edilmiştir. Yirmi dört ay sonra, 100 mW/cm² ışık yoğunluğu altında gerçekleştirilen ölçümlerde fotodedektörün belirgin bir fotocevap sergilemeye devam ettiği görülmüştür. Bu koşullarda, −4 V'ta R = 0,33 A/W, S = 3,3 × 10², EQE = %74 ve D* = 5,8 × 10¹⁰ Jones değerleri elde edilmiştir. Başlangıç ve 24 ay sonraki ölçümlerin benzer ışık yoğunluklarında gerçekleştirilmiş olması, aygıtın uzun bir bekletme süresi sonrasında fotodedeksiyon davranışının karşılaştırmalı olarak değerlendirilmesine imkân sağlamaktadır. Elde edilen sonuçlar, bizmut katkılı GQD tabanlı heteroeklemin 24 aylık bekletme sonrasında genel fotodedeksiyon işlevselliğini büyük ölçüde koruduğunu göstermektedir.

Anahtar kelimeler: Bizmut katkılı grafen kuantum noktaları, heteroeklem, fotodedektör, fotodedeksiyon performansı, uzun dönem performans.

ABSTRACT

Graphene quantum dots (GQDs) have attracted considerable attention for optoelectronic applications due to their tunable electronic and optical properties, high surface area, and compatibility with environmentally friendly synthesis approaches. Heteroatom doping of GQDs provides an effective strategy for tailoring their electronic structure and charge-transport properties, thereby improving photodetector performance. In particular, bismuth doping offers potential for modulating the electronic properties of GQD-based structures and enhancing photoinduced charge transport. In this study, the photodetection performance of a bismuth-doped GQD-based heterojunction was investigated after a 24-month period and compared with its initial photodetection characteristics. The initial measurements were performed under an illumination intensity of 96 mW/cm², whereas the measurements after 24 months were carried out at 100 mW/cm². Photodetector performance was evaluated in terms of responsivity (R), sensitivity (S), external quantum efficiency (EQE), and specific detectivity (D*). The initial measurements revealed a systematic increase in reverse current with increasing illumination intensity, confirming a pronounced photoresponse of the device. At an illumination intensity of 96 mW/cm² and −4 V, R = 0.12 A/W, S = 9 × 10², EQE = 27%, and D* = 5.6 × 10¹⁰ Jones were obtained.

After 24 months, the measurements performed at 100 mW/cm² showed that the photodetector continued to exhibit a pronounced photoresponse. Under these conditions, R = 0.33 A/W, S = 3.3 × 10², EQE = 74%, and D* = 5.8 × 10¹⁰ Jones were obtained at −4 V. The measurements performed at comparable illumination intensities enable a comparative assessment of the photodetection behavior of the device after an extended period. The results demonstrate that the bismuth-doped GQD-based heterojunction largely retained its overall photodetection functionality after 24 months.
Keywords: Bismuth-doped graphene quantum dots, heterojunction, photodetector, photodetection performance, long-term performance.

GİRİŞ

Fotodedektörler, gelen ışığı elektrik sinyallerine dönüştüren ve optik iletişim, görüntüleme, algılama ve çevresel izleme gibi alanlarda yaygın olarak kullanılan temel optoelektronik cihazlardır. Performansları genellikle responsivite, hassasiyet, spesifik dedektivite ve dış kuantum verimi (EQE) gibi parametreler kullanılarak değerlendirilir. Bu nedenle, verimli fotodedektörlerin geliştirilmesi, etkili fototepki ve güvenilir elektriksel özellikler sağlayan uygun aktif malzemelerin ve cihaz mimarilerinin seçilmesini gerektirir (Sohal, Maity, & Basu, 2021; Zhang, Liu, Gong, Liu, & Chen, 2022).

GQD'ler, ayarlanabilir optik ve elektronik özellikleri, kuantum sınırlama etkileri ve çevre dostu sentez yöntemleriyle üretilebilmeleri nedeniyle optoelektronik uygulamalar açısından ilgi görmektedir. Ayrıca, heteroatom katkılama, kimyasal bileşim ve elektronik durumlarda değişiklikler oluşturarak GQD'lerin elektronik yapısının ve optik tepkisinin modüle edilmesine imkân sağlamaktadır (Im, Kim, Hyeong, Moon, & Bae, 2023). Heteroatom katkılı GQD'lerin heteroeklem yapılarına dahil edilmesi, yük taşınımının kontrol edilmesine ve fotodedeksiyon özelliklerinin geliştirilmesine imkân sağlayabilir. Özellikle GQD tabanlı malzemelere bizmut katkılanması, malzemenin elektronik özelliklerinin modüle edilmesine ve bunun heteroeklemin fototepkisi üzerindeki etkilerinin araştırılmasına imkân sağlamaktadır (Berktaş vd., 2026).

Fotodedektörlerin başlangıç performanslarının yanı sıra, uzun dönemli işlevsel davranışları da potansiyel pratik uygulamaları açısından önemli bir husustur. Zaman içinde akım-gerilim karakteristiklerinde ve fotodedeksiyon parametrelerinde meydana gelen değişiklikler, bir cihazın ışıkla indüklenen elektriksel sinyalleri üretme ve algılama yeteneğini koruyup korumadığı hakkında bilgi sağlayabilir. Bu nedenle, uzun bir bekletme süresi sonrasında fotodedektör karakteristiklerinin incelenmesi, cihazın uzun dönemli davranışının değerlendirilmesi açısından önem taşımaktadır (Kielar, Dhez, Pecastaings, Curutchet, & Hirsch, 2016).

Bu çalışmada, bizmut katkılı GQD tabanlı bir heteroeklemin 24 aylık bekletme sonrasındaki fotodedeksiyon davranışı araştırılmıştır. Başlangıç fotodedeksiyon sonuçları önceki çalışmamızda (Berktaş vd., 2026) raporlanmış olup, bu çalışma cihazın 24 ay sonraki karakterizasyonuna ve başlangıç sonuçlarıyla karşılaştırılmasına odaklanmaktadır. Fotodedeksiyon performansı; responsivite (R), hassasiyet (S), dış kuantum verimi (EQE) ve spesifik dedektivite (D*) parametreleri kullanılarak değerlendirilmiştir. Başlangıç ölçümleri 96 mW/cm² ışık yoğunluğu altında gerçekleştirilirken, 24 ay sonraki ölçümler 100 mW/cm² ışık yoğunluğu altında gerçekleştirilmiştir. Birbirine yakın ışık yoğunluklarında gerçekleştirilen bu ölçümler, cihazın uzun dönemli fotodedeksiyon davranışının karşılaştırmalı olarak değerlendirilmesine imkân sağlamaktadır.

YÖNTEM

Çevre dostu bir sentez yaklaşımı olan hidrotermal yöntem kullanılarak Bi katkılı GQD'ler sentezlenmiştir. Sentez işlemi iki aşamada gerçekleştirilmiştir. İlk aşamada, sitrik asit öncülü kullanılarak yüksek sıcaklık ve basınç altında otoklav içerisinde reaksiyon gerçekleştirilmiş ve GQD'ler elde edilmiştir. İkinci aşamada, bizmut(III) nitrat öncülü ile GQD'lerin sulu çözeltisi otoklav içerisinde 90 °C'de 2 saat süreyle reaksiyona tabi tutulmuş ve Bi katkılı GQD'ler elde edilmiştir.

Bi katkılı GQD'lerin sentezlenmesinin ardından, p-tipi silikon alttaş kullanılarak fotodedektör yapısı oluşturulmuştur. İlk olarak, p-tipi silikon alttaşın alt yüzeyine sputtering yöntemiyle altın (Au) kaplanarak omik kontak oluşturulmuştur. Daha sonra, Bi katkılı GQD'ler spin-coating yöntemiyle p-tipi silikon alttaşın üst yüzeyine kaplanmıştır. Son aşamada, Bi katkılı GQD tabakasının üzerine sputtering yöntemiyle Au kaplanarak doğrultucu kontak oluşturulmuş ve fotodedektör yapısı tamamlanmıştır.

ARAŞTIRMA BULGULARI VE TARTIŞMA

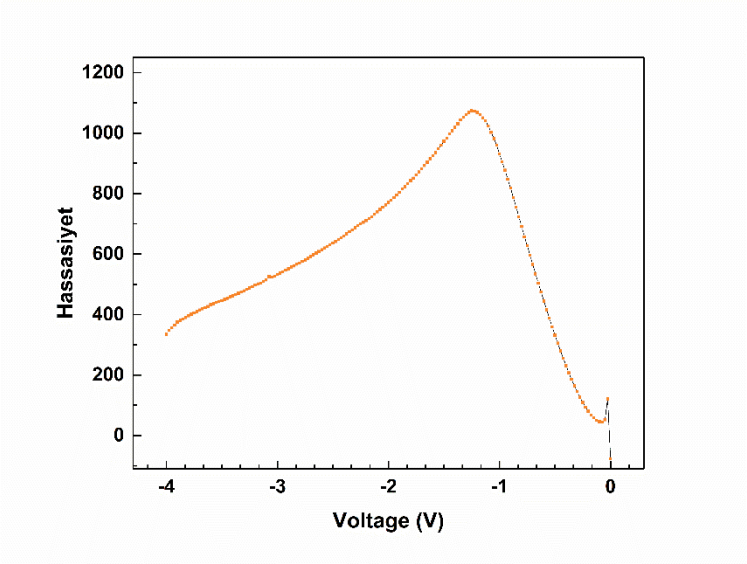
Bu çalışmada, Bi katkılı GQD tabanlı fotodiyotun 24 aylık bekletme sonrasındaki fotodedeksiyon performansı incelenmiş ve elde edilen sonuçlar başlangıç ölçümleriyle karşılaştırılmıştır. Bi katkılı GQD tabanlı heteroeklemin başlangıç fotodedeksiyon özellikleri daha önceki çalışmamızda (Berktaş vd., 2026) raporlanmış olup, bu değerler 24 ay sonra gerçekleştirilen ölçümlerle karşılaştırmada referans olarak kullanılmıştır.

Başlangıç ölçümlerinin ardından cihaz, dış ortamla doğrudan temasını sınırlandıracak şekilde üstü kapalı bir ortamda 24 ay süreyle bekletilmiştir. Bu sürenin sonunda fotodedektör karakterizasyonu yeniden gerçekleştirilmiştir. Başlangıç ve 24 ay sonraki karakterizasyonlar farklı laboratuvarlarda ve farklı ölçüm sistemleri kullanılarak gerçekleştirilmiştir. Başlangıç ölçümleri 96 mW/cm², 24 ay sonraki ölçümler ise 100 mW/cm² ışık yoğunluğu altında gerçekleştirilmiştir. Birbirine yakın ışık yoğunluklarında gerçekleştirilen bu ölçümler, Bi katkılı GQD tabanlı fotodedektörün 24 aylık bekletme sonrasındaki fotodedeksiyon davranışının başlangıç karakteristikleriyle karşılaştırmalı olarak değerlendirilmesine imkân sağlamıştır. Fotodedektör performansı; R, S, EQE ve D* parametreleri kullanılarak değerlendirilmiştir.

Hassasiyet (S), cihazın aydınlatma altında oluşturduğu akım değişiminin karanlık durumdaki akıma göre büyüklüğünü ifade eder ve Denklem (1) kullanılarak hesaplanır:

$$S = \frac{I_{light} - I_{dark}}{I_{dark}} \qquad (1)$$

Burada I_{light} ve I_{dark}, sırasıyla aydınlatılmış ve karanlık koşullarda ölçülen akımlardır. Şekil 1'de hassasiyetin uygulanan gerilime bağlı değişimi verilmiştir. Negatif gerilim bölgesinde hassasiyetin gerilime bağlı olarak belirgin bir değişim gösterdiği ve yaklaşık −1,2 V civarında maksimum değerine ulaştığı görülmektedir. Bu gerilimde hassasiyet yaklaşık 1,1 × 10³ değerine ulaşmaktadır. Maksimum noktanın her iki tarafında hassasiyet azalmakta ve özellikle gerilimin 0 V'a yaklaşmasıyla bu azalma daha belirgin hale gelmektedir. Bu sonuçlar, fotodedektör hassasiyetinin uygulanan gerilime güçlü bir şekilde bağlı olduğunu ve incelenen gerilim aralığında en yüksek hassasiyetin yaklaşık −1,2 V civarında elde edildiğini göstermektedir.



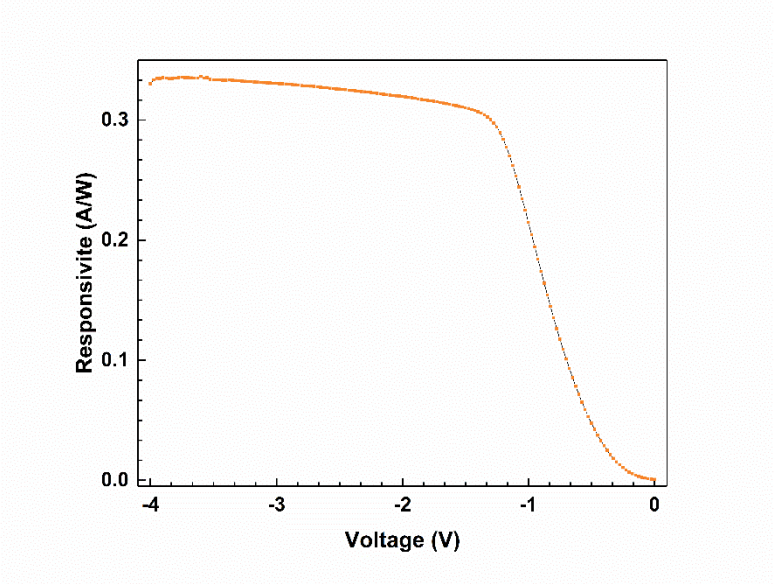
Şekil 1. Bi katkılı GQD hibrit yapının uygulanan gerilime bağlı hassasiyet (S) değişimi.

Responsivite (R), fotodedektör tarafından üretilen fotoakımın gelen optik güce oranını ifade eder ve Denklem (2) kullanılarak hesaplanır:

$$R = \frac{I_{photo}}{P_{opt}} = \frac{I_{light} - I_{dark}}{E_{inc}.A} \qquad (2)$$

Burada I_{photo} fotoakım, E_{inc} gelen ışık yoğunluğu (mW cm^{-2}), A diyot alanı ve P_{opt} gelen optik güçtür. Şekil 2'de responsivitenin uygulanan gerilime bağlı değişimi verilmiştir. Responsivitenin yaklaşık −4 V ile −1,5 V arasındaki negatif gerilim bölgesinde 0,30–0,34 A/W aralığında kaldığı görülmektedir. Gerilimin 0 V'a yaklaşmasıyla responsivite belirgin biçimde azalmakta ve sıfıra yaklaşmaktadır. Bu

sonuçlar, cihazın responsivitesinin yüksek negatif gerilim bölgesinde uygulanan gerilime karşı nispeten kararlı bir davranış sergilediğini göstermektedir.

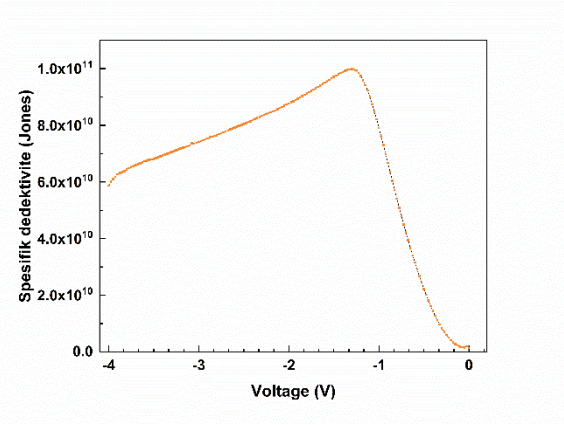


Şekil 2. Bi katkılı GQD hibrit yapının uygulanan gerilime bağlı responsivite (R) değişimi.

Spesifik dedektivite (D*), fotodedektörün düşük seviyeli optik sinyalleri gürültüden ayırt ederek algılama kabiliyetini ifade eden önemli bir performans parametresidir ve Denklem (3) kullanılarak hesaplanır:

$$D^* = \frac{\sqrt{A\,x\,\Delta f}}{NEP} = R\,x\,\frac{\sqrt{A\,x\,\Delta f}}{i_{noise}} \qquad (3)$$

Burada A diyot alanını, q elektron yükünü, R responsiviteyi, i_n gürültü akımını ve Δf elektriksel bant genişliğini ifade etmektedir. Spesifik dedektivitenin uygulanan gerilime bağlı değişimi Şekil 3'te gösterilmiştir. D* değerinin negatif gerilim bölgesinde gerilime bağlı olarak belirgin bir değişim gösterdiği ve yaklaşık −1,3 V civarında $1{,}0 \times 10^{11}$ Jones ile maksimum değerine ulaştığı görülmektedir. Maksimum değerin ardından, gerilimin 0 V'a yaklaşmasıyla D* değerinde belirgin bir düşüş meydana gelmekte ve değer sıfıra yaklaşmaktadır. Bu sonuçlar, incelenen gerilim aralığında en yüksek spesifik dedektivitenin yaklaşık −1,3 V civarında elde edildiğini göstermektedir.



Şekil 3. Bi katkılı GQD hibrit yapının uygulanan gerilime bağlı spesifik dedektivite (D*) değişimi.

Başlangıç ve 24 ay sonraki fotodedektör karakterizasyonunda −4 V'ta elde edilen performans değerleri Tablo 1'de karşılaştırmalı olarak sunulmuştur. Başlangıç performans değerleri daha önce yayımlanan çalışmamızdan (Berktaş vd., 2026) alınmış olup, söz konusu çalışmaya ait grafikler bu çalışmada yeniden kullanılmamıştır. Bunun yerine, başlangıç ve 24 ay sonraki karakterizasyon sonuçları sayısal

olarak karşılaştırılmıştır. Başlangıç karakterizasyonunda, 96 mW/cm² ışık yoğunluğu altında R, S, EQE ve D* değerleri sırasıyla 0,12 A/W, 9×10^2, %27 ve $5,6 \times 10^{10}$ Jones olarak raporlanmıştır (Berktaş vd., 2026). Yirmi dört ay sonra, 100 mW/cm² ışık yoğunluğu altında elde edilen R, S, EQE ve D* değerleri ise sırasıyla 0,33 A/W, $3,3 \times 10^2$, %74 ve $5,8 \times 10^{10}$ Jones olarak belirlenmiştir.

Tablo 1. Bi katkılı GQD hibrit yapının başlangıç ve 24 ay sonraki fotodedektör performansının karşılaştırılması.

Fotodedektör performans metriği	**Başlangıç ölçümü (96 mW/cm²)**	**24 ay sonraki ölçüm (100 mW/cm²)**
Hassasiyet, S	9×10^2	$3,3 \times 10^2$
Responsivite, R (A/W)	0,12	0,33
Spesifik dedektivite, D* (Jones)	$5,6 \times 10^{10}$	$5,8 \times 10^{10}$
Dış kuantum verimi, EQE (%)	27	74

Spesifik dedektivite değerindeki sınırlı değişim, cihazın 24 aylık bekletme sonrasında algılama kabiliyetini büyük ölçüde koruduğunu göstermektedir. Responsivite ve EQE değerlerindeki artış ise cihazın 24 ay sonra da ölçüm koşulları altında güçlü bir fotocevap sergilemeye devam ettiğini ortaya koymaktadır.

Genel olarak elde edilen sonuçlar, Bi katkılı GQD tabanlı heteroeklemin 24 aylık bekletme sonrasında fotodedektör işlevselliğini büyük ölçüde koruduğunu göstermektedir. Özellikle spesifik dedektivitenin başlangıç değerine yakın kalması, cihazın düşük seviyeli optik sinyalleri algılama kabiliyetinin korunduğuna işaret etmektedir. Bununla birlikte, hassasiyet değerinde gözlenen azalma, fotodedeksiyon parametrelerinin tamamının aynı eğilimi göstermediğini ortaya koymaktadır. Başlangıç ve 24 ay sonraki ölçümlerin farklı ölçüm sistemleri kullanılarak gerçekleştirilmiş olması nedeniyle, gözlenen değişimlerin yalnızca bekletme süresinden kaynaklandığı şeklinde doğrudan bir değerlendirme yapılmamalıdır.

SONUÇ

Bu çalışmada, hidrotermal yöntemle sentezlenen Bi katkılı GQD'ler kullanılarak p-tipi Si tabanlı bir heteroeklem fotodedektör oluşturulmuş ve cihazın fotodedeksiyon performansı 24 aylık bekletme sonrasında yeniden incelenmiştir. Başlangıç ve 24 ay sonraki karakterizasyonlarda farklı ölçüm sistemlerinin ve birbirine yakın ancak aynı olmayan ışık yoğunluklarının kullanılması nedeniyle, elde edilen sonuçlar tamamen aynı deneysel koşulları temsil etmemektedir. Bu nedenle, fotodedeksiyon parametrelerinde gözlenen değişimlerin yalnızca 24 aylık bekletme süresinden kaynaklandığı şeklinde kesin bir nedensellik kurulması uygun değildir.

Bununla birlikte, 24 ay sonraki ölçümlerde cihazın belirgin bir fotocevap sergilemeye devam ettiği görülmüştür. Responsivite ve EQE değerleri başlangıç ölçümlerine göre daha yüksek değerler gösterirken, spesifik dedektivite başlangıç değerine yakın kalmış, hassasiyet ise azalmıştır. Bu sonuçlar, farklı performans parametrelerinde farklı değişimler gözlenmesine rağmen, Bi katkılı GQD tabanlı heteroeklemin 24 aylık bekletme sonrasında fotodedektör işlevselliğini büyük ölçüde koruduğunu göstermektedir. Elde edilen bulgular, Bi katkılı GQD tabanlı heteroeklemlerin uzun dönemli optoelektronik uygulamalardaki potansiyelinin değerlendirilmesi açısından önemli bir gösterge sunmaktadır.

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HETEROATOM DOPING OF PEM FUEL CELL ELECTROCATALYST MATERIALS

PEM YAKIT PİLİ ELEKTROKATALİZÖRLERİNDE HETEROATOM KATKILAMA

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ABSTRACT

In proton exchange membrane fuel cells (PEMFCs), the high cost of platinum-based catalysts and the slow kinetics of the oxygen reduction reaction (ORR) occurring at the cathode necessitate the development of electrocatalysts that are more active and durable, and possess higher Pt utilization efficiency. In this context, this review evaluates the effects of nitrogen (N), sulfur (S), and phosphorus (P) doping on carbon-supported Pt and Pt-based bimetallic electrocatalysts, particularly regarding metal–support interactions, catalyst layer structure, ORR performance, and durability. Recent studies demonstrate that the effects of heteroatom doping cannot be explained solely by the total heteroatom content; the structural configuration of the heteroatom, the synthesis method, the structure of the carbon support, and the properties of the metallic phase are also determining factors. While N-doping can alter surface chemistry, metal coordination, and support–ionomer interactions, S-modification can regulate ionomer distribution, proton accessibility, oxygen transport, and interfacial charge transfer. P-doping, on the other hand, is particularly associated with strengthening the Pt–support interaction, limiting nanoparticle migration, and enhancing long-term electrochemical stability. However, improvements in ORR activity and durability cannot be attributed solely to heteroatom doping, as alloy composition, particle size, and support structure also simultaneously influence catalytic performance. Therefore, future catalyst designs must consider the heteroatom type and configuration in conjunction with metal–support interactions, low Pt loading, transport processes within the catalyst layer, and long-term operational stability in PEMFCs.

Keywords: Electrocatalyst, heteroatom, carbon support materials

ÖZET

Proton değişim membranlı yakıt hücrelerinde (PEMFC'ler), platin bazlı katalizörlerin yüksek maliyeti ve katotta gerçekleşen oksijen indirgenme reaksiyonunun (ORR) yavaş kinetiği; daha aktif, daha dayanıklı ve daha yüksek Pt kullanım verimliliğine sahip elektrokatalizörlerin geliştirilmesini zorunlu kılmaktadır. Bu bağlamda söz konusu derleme; özellikle metal-destek etkileşimleri, katalizör katmanı yapısı, ORR performansı ve dayanıklılık açısından, karbon destekli Pt ve Pt tabanlı bimetalik elektrokatalizörler üzerindeki azot (N), kükürt (S) ve fosfor (P) katkılamasının etkilerini değerlendirmektedir. Yakın tarihli çalışmalar, heteroatom katkılamasının etkilerinin yalnızca toplam heteroatom içeriğiyle açıklanamayacağını; heteroatomun yapısal konfigürasyonu, sentez yöntemi, karbon desteğin yapısı ve metalik fazın özelliklerinin de belirleyici faktörler olduğunu göstermektedir. N-katkılama yüzey kimyasını, metal koordinasyonunu ve destek-iyonomer etkileşimlerini değiştirebilirken; S-modifikasyonu iyonomer dağılımını, proton erişilebilirliğini, oksijen taşınımını ve arayüzey yük transferini düzenleyebilir. Öte yandan P-katkılama; özellikle Pt-destek etkileşiminin güçlendirilmesi, nanoparçacık göçünün sınırlandırılması ve uzun vadeli elektrokimyasal kararlılığın artırılması ile ilişkilidir. Bununla birlikte, ORR aktivitesi ve dayanıklılığındaki iyileşmeler yalnızca heteroatom katkılamasına atfedilemez; zira alaşım bileşimi, parçacık boyutu ve destek yapısı da katalitik performansı eş zamanlı olarak etkilemektedir. Bu nedenle, gelecekteki katalizör tasarımları; metal-destek etkileşimleri, düşük Pt yüklemesi, katalizör katmanı içindeki taşınım süreçleri ve PEMFC'lerdeki uzun vadeli operasyonel kararlılıkla birlikte heteroatom türü ve konfigürasyonunu da dikkate almalıdır.

Anahtar kelimeler: Elektrokatalizör, heteroatom, karbon destek malzemeleri

1. INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are electrochemical systems that convert chemical energy directly into electrical energy and hold significant potential for various application areas. The efficient and stable operation of these systems depends on the kinetics of the electrochemical reactions occurring at the electrodes and the properties of the electrode materials used. In particular, the relatively slow kinetics of the oxygen reduction reaction (ORR) at the cathode is one of the main factors limiting PEMFC performance **(**Luo & Koper, 2022).

Support materials used in the catalyst layer of PEM fuel cells play a crucial role in establishing electron transport pathways within the electrode. In carbon-supported catalysts, the carbon network formed by the support materials creates the electron transport channel within the membrane electrode assembly (MEA), while catalytic particles are dispersed across the carbon surface (Figure 1). Carbon supports have to provide high surface area, high electrical conductivity and good metal-support interactions for high electrocatalyst activity.

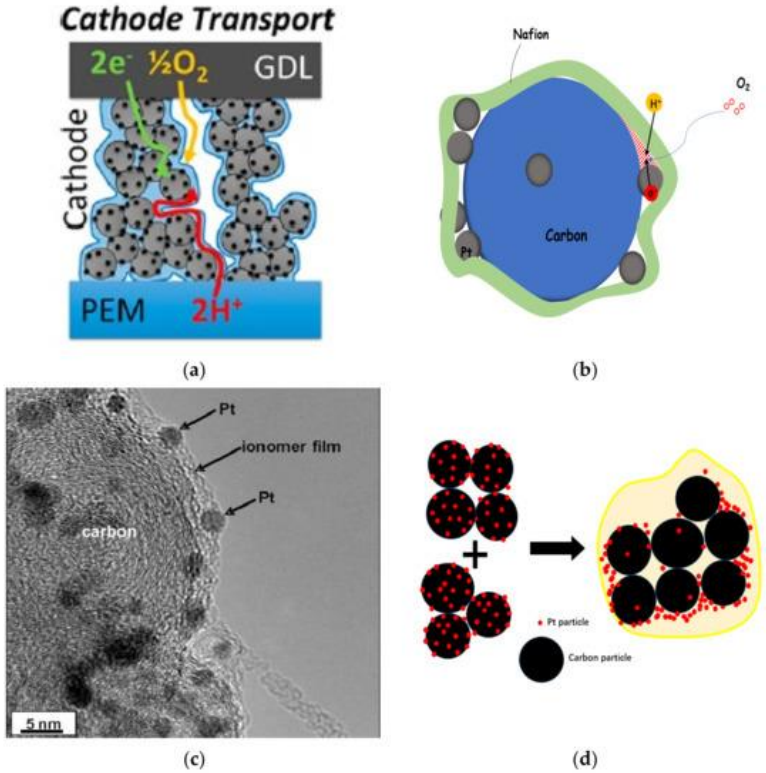


Figure 1. (a) Schematic representation of the structure and electron and proton transport on the cathode side of the MEA. (b) Schematic representation of the three-phase boundary region at the PEMFC cathode. (c) Microscopic image of the Pt particle–ionomer–carbon support microstructure. (d) Schematic representation of the secondary distribution of Pt nanoparticles on the support during the preparation of the catalyst layer (Xie et al., 2021).

The structure of the catalyst layer consists of particles, aggregates, and pores of varying sizes. Carbon support particles typically form aggregates through the binding action of the ionomer, with catalytic particles dispersed on the surfaces of these aggregates. Adequate transport pathways must exist within the catalyst layer to facilitate the transport of electrons, protons, reactant gases, and product water. Consequently, the carbon support structure, ionomer distribution, and the resulting porous structure constitute the fundamental components of the catalyst layer's structural characteristics (Xie et al., 2021). Platinum (Pt)-based materials are among the primary electrocatalysts in PEMFC cathodes due to their high ORR activity. However, the cost of Pt, its limited availability, and potential performance losses under prolonged operating conditions necessitate the development of more efficient and robust catalysts. Accordingly, reducing the amount of Pt, alloying with a second metal or creating intermetallic structures, and controlling the electronic and structural properties of the catalyst are considered among the main material design strategies (Kim et al., 2024; Song et al., 2022; Xue et al., 2024).

Combining Pt with transition metals such as Ni, Co, Cu, and Fe to reduce Pt usage while simultaneously increasing ORR activity is an important catalyst design approach. The electrocatalytic performance of these PtM (M= Ni, Co, Cu, Fe, etc.) alloy nanostructures is influenced by interrelated factors such as the arrangement of the d-band center, strain effect, particle size, and surface structure. These electronic and structural changes can alter ORR kinetics by regulating the interaction of Pt active sites with intermediate species. However, despite high platinum utilization and significant advances in bulk activity, achieving high activity along with long-term durability remains a significant challenge for PEMFC electrocatalysts (Kim et al., 2024).

New active sites in electrocatalysts can also be achieved via heteroatom doping which is an important approach for modifying surface properties, electronic structure, metal-support interaction, active center formation, and catalyst stability in PEM fuel cell electrocatalysts (Figure 2). This paper discusses the effects of heteroatom doping on the electronic and structural properties of Pt and Pt-based bimetallic electrocatalysts. Furthermore, based on current literature studies, the relationships between catalyst structure, heteroatom type, ORR performance, and electrochemical stability are evaluated.

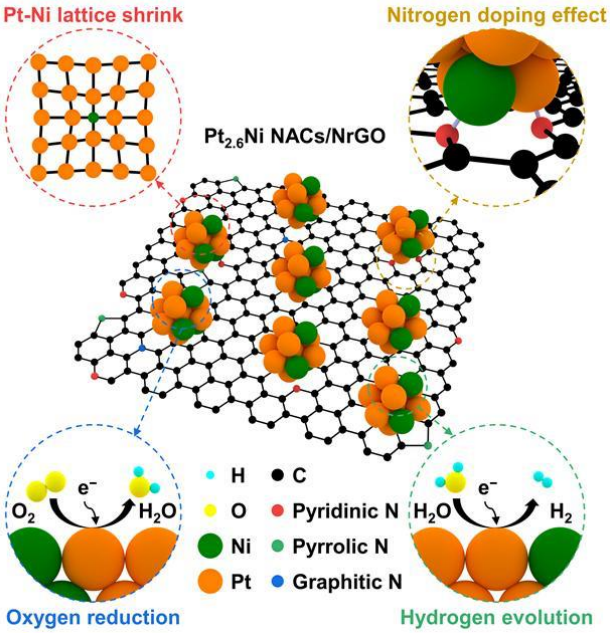


Figure 2. Schematic representation of a Pt–Ni catalyst supported on nitrogen-doped carbon

2. EFFECTS OF HETEROATOM DOPING ON THE PROPERTIES OF ELECTROCATALYTIC MATERIALS

The addition of heteroatoms to carbon structures can alter the electronic and surface properties of the carbon support, contributing to the regulation of the interaction between metal nanoparticles and the support. Heteroatom-doped carbon supports can have positive effects on ORR activity and electrochemical resistance by promoting more efficient attachment of metal species and the establishment of a stable structure for alloy nanoparticles (Zhang et al., 2023).

2.1. Nitrogen Addition

Nitrogen (N) doping is one of the approaches used to modify support-ionomer interactions within the catalyst layer and the surface properties of the carbon support in PEMFC cathode catalysts. Nitrogen-doped carbon supports can contain different types of nitrogen (Figure 3), and the resulting surface properties can vary depending on the nitrogen source used and the synthesis method applied. Therefore, evaluating the effect of N-doped carbon supports on PEMFC performance solely based on the total nitrogen content is insufficient.

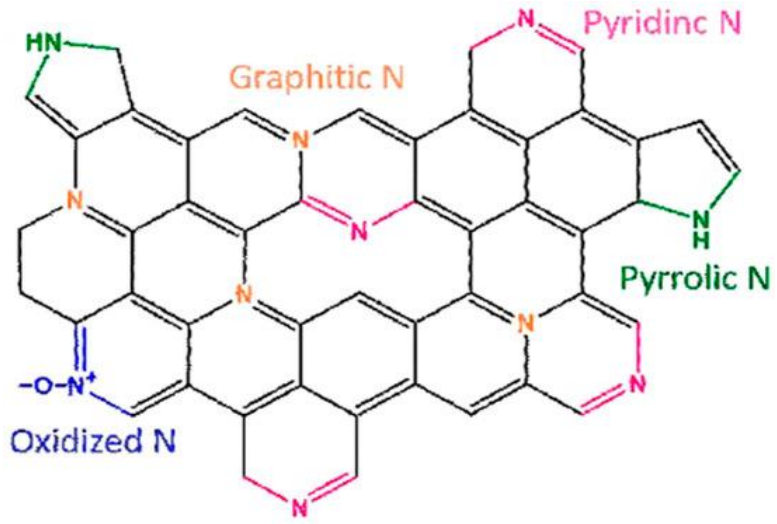


Figure 3. The four nitrogen doping configurations usually observed on carbon catalysts (Zhou et al., 2018)

Ott et al. demonstrated that in N-doped high surface area carbon supports prepared using different nitrogen precursors, the nitrogen source and modification method significantly affect the physicochemical properties of the support and the resulting catalyst layer behavior. In this study, the interaction of N-doped carbons with the ionomer was evaluated using electrochemical surface area, proton resistance, cell performance under humidity conditions, and limiting current measurements. XPS results revealed an interaction between the basic N groups on the carbon surface and the acidic side chains of the ionomer. Furthermore, it was determined that the presence of only N-containing surface groups did not guarantee a more homogeneous or suitable ionomer distribution; the resulting effect depended on the N precursor used and the changes in the physicochemical properties of the carbon support caused by the synthesis pathway (Ott et al., 2022). It has been reported that these changes can affect PEMFC performance by influencing proton transport and other transport resistances in the catalyst layer.

The effect of nitrogen doping on the performance and stability of Pt-based catalysts under PEMFC operating conditions was also investigated by Hornberger et al. It was reported that the ORR activity and stability of Pt/N-C catalysts prepared by depositing highly homogeneous Pt nanoparticles onto N-doped carbons were comparable to those of current PEMFC catalysts. The study, which combined electrochemical measurements in a liquid electrolyte environment with single-cell membrane electrode assemblies (MEAs), revealed that the effect of N doping cannot be explained solely by conventional electrochemical tests. It has been determined that N-doped carbon supports can improve cell performance, especially under conditions of 0.6–0.9 V, which is the normal operating range of PEMFCs (Hornberger et al., 2022). However, the effect of N addition on the strength of the carbon support was not found to be in the same direction. Hornberger et al. showed that the addition of nitrogen heteroatoms to the carbon structure was not sufficient to prevent carbon corrosion in high-potential cycles between 1.0–1.5 V. Therefore, although N addition can improve catalyst performance under normal PEMFC operating conditions (0.6–0.9 V), it does not provide a direct protective effect against the degradation of the carbon support at high potentials (Hornberger et al., 2022).

In the literature, two different nitrogen doping strategies were followed. In the first case, Pt electrocatalysts were synthesized over nitrogen doped carbon materials and in the second case synthesized Pt electrocatalysts were nitrogen doped. It was observed that nitrogen doping of electrocatalysts showed better PEMFC performance when compared to the nitrogen doping of carbon supports (Çelik & Bayrakçeken, 2025).

It is seen that the effect of N doping in PEMFCs cannot be attributed solely to nitrogen content or the amount of a specific type of N. The N precursor used and the support-ionomer interaction that occurs with the synthesis method, surface properties, and proton and mass transport processes in the catalyst layer are interconnected factors that determine the cell performance of N-doped carbon supports (Ott et al., 2022). Furthermore, while N additives can improve cell performance under normal PEMFC

operating conditions, they are not sufficient on their own to prevent carbon corrosion occurring at high operating potentials (Hornberger et al., 2022).

2.2. Sulfur Addition

Sulfur (S)-modified carbon structures can be used in PEMFC cathodes not only as a support material that alters the environment of the catalytic phase, but also as an approach that can regulate metal-support and ionomer-support interactions within the catalyst layer. Zhang et al. demonstrated that modification of the carbon support with thiophenic-S groups could alter the distribution of the PFSA ionomer on the catalyst layer. The interaction between the thiophenic-S sites and the sulfonic acid-containing side chains of the ionomer contributed to a more favorable distribution of the ionomer on the Pt_3Co/S–KB catalyst (Figure 4). This improved accessibility of the catalytic sites to proton transport pathways while reducing resistance to oxygen transport (Zhang et al., 2025). This study contributed to the more effective utilization of active Pt sites at lower Pt loadings and the improvement of three-phase reaction sites in the catalyst layer. The study reported that MEA containing Pt_3Co/S–KB achieved a nominal power density of 1.06 W cm^{-2} at 0.67 V under H_2/air conditions (Zhang et al., 2025). Based on the results, it is predicted that the effect of S modification in PEMFCs should be evaluated not only in terms of ORR kinetics but also in conjunction with electrode-level processes such as proton accessibility, oxygen transport, and catalyst-ionomer interface.

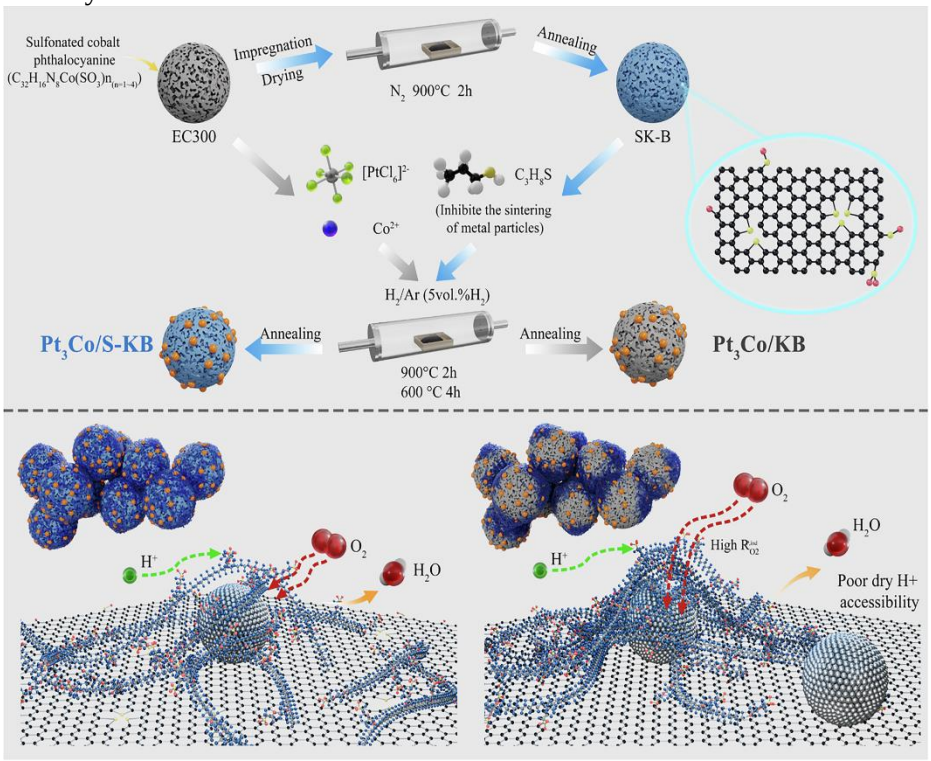


Figure 4. Top Image: Synthesis process of Pt-Co alloy catalyst supported by small molecule-assisted impregnation onto conventional carbon support EC300 (indicated by the gray arrow) and modified S-KB (indicated by the blue arrow). The main difference is that S-KB is modified with thiophene S. Bottom Images: Pt_3Co/S-KB (bottom left image) and Pt_3Co/KB (bottom right image) (Zhang et al., 2025).

Another important effect of sulfur doping in PEMFC electrocatalysts is related to the regulation of interfacial interactions between metal nanoparticles and carbon support. Niu et al. developed a three-dimensional ORR catalyst with low Pt content by modifying a Pt–Co nanoalloy with an S-doped Co–N–C structure. In this study, it was stated that the co-doping of N and S can enhance the metal-support interaction between Pt/Pt–Co and S-doped Co–N–C by regulating charge transfer at the interface (Niu et al., 2024). This integrated structure demonstrated electrochemical stability and improved ORR activity when compared to commercial Pt/C. Therefore, this study reveals that sulfur (S) doping can contribute to the regulation of the metal-support interface in Pt–Co-based systems, and this can play a role in improving catalytic activity and stability (Niu et al., 2024).

When the literature studies are evaluated together, explaining the sulfur doping in PEMFC electrocatalysts through a single mechanism is not considered sufficient. Sulfur-containing carbon structures contribute to the regulation of ionomer distribution in the catalyst layer and can also affect interfacial interactions and charge transfer between Pt-based structures and the support. Therefore, the contribution of sulfur modification to PEMFC performance should be evaluated within the framework of interconnected processes such as metal-support interaction, ORR activity, proton accessibility, Pt utilization efficiency, and oxygen transport (Niu et al., 2024; Zhang et al., 2025).

2.3. Phosphorus Addition

Phosphorus (P) doping is used in PEMFC electrocatalysts to both improve the stability of the Pt-based active phase and enhance the interaction of the carbon support with Pt nanoparticles. Shen et al. demonstrated that phosphorus in a P-doped PtCo/C catalyst contributes to the improvement of ORR performance, and especially long-term stability, by modifying the electronic and structural properties of PtCo nanoparticles. A bulk activity of 0.72 Å $mgPt^{-1}$ was obtained at 0.9 V in the P5–PtCo/C catalyst, which is 4.5 times higher than that of commercial Pt/C. Furthermore, the loss in bulk activity after 30,000 potential cycles was determined to be only 9.4% (Shen et al., 2023). These results demonstrate that P doping can contribute to maintaining the stability of PtCo nanoparticles under electrochemical conditions.

Phosphorus can improve the ability of carbon supports to retain Pt nanoparticles in PEMFC catalysts. Kim et al. reported that doping a carbon support with a high crystalline structure and inherent hydrophobic properties with phosphorus resulted in more effective stabilization of Pt nanoparticles on the support surface (Figure 5). Phosphorus-containing regions strengthened the Pt-support interaction, limiting the movement of Pt nanoparticles and associated structural changes, thereby improving the long-term electrochemical stability of the catalyst. The Pt/HCCp (HCCp: phosphorus-doped high crystalline carbon support) catalyst showed only a 2 mV half-wave potential shift and a 1.9% electrochemical surface area loss after 20,000 cycles of endurance testing. In single-cell tests, it was reported that 92.4% of the initial power density was retained (Kim et al., 2026).

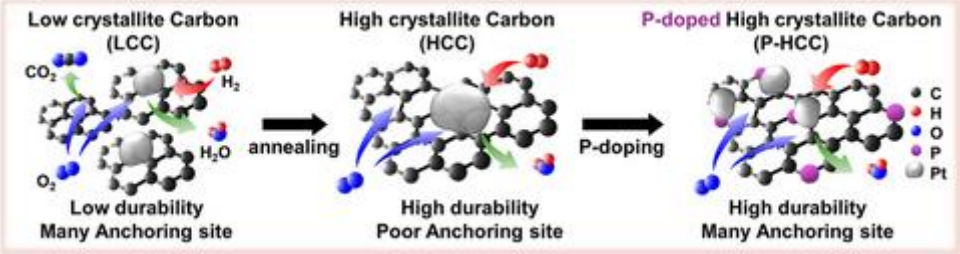


Figure 5. Relationship between durability, carbon defects, and Pt binding points in various carbon supports (Kim et al., 2026).

When these literature studies are evaluated together, it is seen that phosphorus doping in PEMFC electrocatalysts is not limited to simply increasing ORR activity. The fact that P improves the stability of the PtCo-based active phase and contributes to the stronger fixation of Pt nanoparticles on the carbon support can help maintain the structural integrity of the catalyst during long-term use. Therefore, phosphorus doping can be considered as an approach to simultaneously improve electrochemical stability and metal-support interaction in Pt-based PEMFC catalysts (Kim et al., 2026; Shen et al., 2023).

2.4. Multiple Heteroatom Doping

The incorporation of multiple heteroatoms into a carbon support is one of the approaches used to regulate metal-support interaction and support structure in Pt-based electrocatalysts. The ORR performance observed in such systems is not solely due to heteroatom doping; metal alloying, structural properties of the carbon support, and metal-support interaction also have a combined effect on the catalytic behavior. Zhang et al. prepared PtCu alloy nanoparticles on N and P-doped carbon supports via microbial adsorption followed by carbonization-reduction. Among the catalysts obtained, PtCu/NPC-700 °C showed the highest ORR performance and reached a mass activity of 0.895 A $mgPt^{-1}$ at 0.9 V. This value has been reported to be approximately 8.29 times that of the commercial Pt/C catalyst (Zhang et al., 2023). The high ORR performance obtained in the study was evaluated based on the catalytic structure formed by the properties of the carbon support containing N and P and the PtCu alloy structure.

Therefore, instead of attributing the performance increase in the PtCu/NPC system solely to the N and P additions, the combined effect of the co-added carbon support and the PtCu alloy is considered.

The effect of multi-doped carbon supports on Pt-based intermetallic catalysts was investigated by Lu et al. on a Pt_2CuFe system. In this study, a multi-doped carbon support containing Pt, Cu, Fe, Cr, S, and N formed strong metal-support interactions with Pt_2CuFe clusters, limiting particle growth during high-temperature heat treatment. Highly ordered Pt_2CuFe intermetallic nanoparticles with a size of approximately 2.2 nm were obtained even after annealing at 800 °C. The prepared Pt_2CuFe/MHC (MHC: multi-heteroatom doped carbon) catalyst showed a mass activity of 2.07 Å $mgPt^{-1}$ ORR and retained 64% of its initial mass activity after 40,000 voltage cycles. In MEA tests, a peak power density of 1.29 W cm^{-2} was reached under H_2/air conditions, and a voltage drop of only 25 mV was determined at a current density of 0.8 A cm^{-2} (Lu et al., 2026).

It can be seen that carbon supports containing multiple heteroatoms can improve the stability of metal nanoparticles on the support and the metal-support interaction in Pt-based catalysts. However, since the effects of heteroatom addition and alloy or intermetallic structure occur together in systems such as Pt_2CuFe/MHC and PtCu/NPC, it is not appropriate to consider the observed increase in ORR activity and strength as solely the effect of a specific heteroatom (Lu et al., 2026; Zhang et al., 2023).

3. HETEROATOM-DOPED CARBON SUPPORTS and Pt-BASED BIMETALLIC CATALYSTS

The use of heteroatom-doped carbon supports in combination with Pt-based bimetallic catalysts represents a significant approach to regulating the interaction between the active metal phase and the carbon support. In these systems, catalytic performance depends not only on the alloy structure between Pt and the second metal, but also on the interface formed by the metal nanoparticles with the carbon support, which can play a decisive role in activity and stability.

Huang et al. designed a catalyst that integrates a Co–N–C matrix containing N with a Pt-based metal phase and reported that the resulting structure exhibits significantly higher ORR bulk activity compared to commercial Pt/C. Furthermore, the high activity retention of the catalyst after long-term potential cycles suggests that modifying the Pt-based active phase with an N-containing carbon matrix may be effective in improving both catalytic activity and stability (Huang et al., 2022).

The effect of the metal-support interface on the electronic structure of Pt was investigated in detail by Xue et al. on PtFe nanocrystals and N-doped carbon supports containing atomically dispersed Fe centers. The PtFe@Fe_{SAs}–N–C catalyst achieved a mass activity of 0.75 A $mgPt^{-1}$ at 0.9 V and a peak power density of 1.24 W cm^{-2} in PEMFC tests. Furthermore, it retained 97% of its initial mass activity after 30,000 cycles and showed no significant current loss for 220 hours at 0.6 V. The study concluded that the interaction between atomic Fe centers on the support and the PtFe alloy regulates the occupancy state of the Pt d-orbital, and this modifies its interaction with ORR intermediates (Xue et al., 2024).

In a similar study, Pt–Ni was investigated together. Yan et al. developed a system in which two different active structures are integrated within the same catalyst by modifying atomically dispersed Ni–N_4 regions with Pt_3Ni nanolattices that have a Pt-rich surface. The study reported that the interaction between Ni–N_4 regions and the Pt_3Ni structure contributed to the improvement of ORR activity and stability (Yan et al., 2023). This result demonstrates that the combination of heteroatom-coordinated metal regions with Pt-based alloy nanoparticles can be effective in regulating catalytic properties.

In determining the stability of metal nanoparticles on a support, not only heteroatom contribution but also binding sites in the carbon structure can be important. Cui et al. fixed approximately 2.6 nm Pt_1Ni_1@Pt/C core-shell nanoparticles on a support by exploiting structural irregularities on the carbon. The strong Pt–C interaction that occurred resulted in the catalyst showing only a 1.6% loss in activity even after 70,000 potential cycles, and prevented the agglomeration of nanoparticles (Cui et al., 2024). This study directly demonstrates that metal-carbon interaction can play a significant role in maintaining nanoparticle size and distribution.

It can be summarized that modifying Pt-based bimetallic or intermetallic structures with heteroatom-doped carbon supports can affect ORR performance in different ways. Heteroatom-containing coordination regions contribute to the improvement and regulation of the electronic properties of the metal-support interface (Huang et al., 2022; Xue et al., 2024; Yan et al., 2023), while strong metal-carbon interactions can also contribute to maintaining structural stability by limiting the agglomeration and migration of nanoparticles (Cui et al., 2024).

Therefore, in PEMFC catalysts where heteroatom doping and bimetallic alloying are used together, strength and activity must be evaluated considering both metal-support interaction and the electronic structure of the metal phase.

The literature studies given above are summarized in Table 1 in order to give a brief information about the effects of heteroatom doping on PEMFC performance.

Catalyst	Heteroatom	Support	Synthesis Approach	PEMFC Performance	Source
Pt/N-C	N	N-functional carbon black	Surface N-modification with different N-precursors; Pt loading and MEA preparation	Some N-modified carbon supports have improved PEMFC performance; this improvement has been shown to be due more to increased oxygen mass transport resulting from the altered pore structure during synthesis than to the N addition itself.	Ott et al., 2022
Pt/N-C	N	Pyridinic-N content adjusted carbon	Controlled N-doping and Pt nanoparticle loading	N addition improved performance under PEMFC operating conditions; this improvement was attributed to improved ionomer distribution due to high pyridinic-N content. However, carbon corrosion resistance was negatively affected.	Hornberger et al., 2022
PtCo@CoNC/NTG (NTG: nitrogen-doped tubular graphene)	N	Co–N–C containing nanocarbon network	Synthesis of multiscale Pt–Co/Co–N–C nanocarbon electrocatalysts.	PtCo@CoNC/NTG achieved a mass activity of 1.52 A $mgPt^{-1}$, 11.7 times that of commercial Pt/C; It showed only a 1.3% loss after 30,000 cycles and provided a power density of 980 mW cm^{-2} at 0.6 V.	Huang et al., 2022
PtCu/NPC-700	N, P	N,P co-doped porous carbon	Pyrolysis of microbial precursor and PtCu loading	PtCu/NPC reached a mass activity of 0.895 A $mgPt^{-1}$ at 700 °C and 0.9 V, which is 8.29 times that of Pt/C; It showed low ECSA and activity losses after 10,000 cycles and exhibited higher activity and resistance than Pt/C in single-cell tests.	Zhang et al., 2023
P5-PtCo/C(5: 5 mg phytic acid)	P	P-doped carbon / PtCo	One-step hydrothermal synthesis using phytic acid.	P5-PtCo/C reached approximately 4.5 times the mass activity of Pt/C with 0.72 A $mgPt^{-1}$ at 0.9 V; Activity loss after 30,000 and 70,000 cycles was 9.4% and 37.7%, respectively. P addition enhanced the PtCo–carbon interaction and catalyst stability.	Shen et al., 2023
Pt–Co/S–Co–N–C	S, N	S-doped Co–N–C	Integration of Pt–Co nanoalloy with S-doped Co–N–C in a 3D hybrid structure	The 3D LPCNSC catalyst, obtained by combining a Pt–Co nanoalloy with an S-doped Co–N–C structure in a three-dimensional architecture, demonstrated higher ORR activity and stability compared to commercial 20% Pt/C despite its lower Pt content	Niu et al., 2024

				of 13.65%. Under H_2/O_2 conditions, the maximum power density reached 983.8 mW cm^{-2}.	
PtFe@Fe_{SAs}–N–C (SAs: single atoms)	N	One-atom Fe–N–C	Formation of ultra-thin PtFe alloy nanocrystals on N-doped carbon (Fe_{SAs}–N–C) containing atomic Fe centers	PtFe@FeSAs-N-C achieved a mass activity of 0.75 A $mgPt^{-1}$ and a peak power density of 1.24 W cm^{-2} at 0.9 V; It maintained 97% of its activity after 30,000 cycles and showed no significant performance loss in a 220-hour PEMFC test.	Xue et al., 2024
Pt_3Co/S-KB (KB: Ketjenblack)	S	Ketjenblack with thiophenic-S modification	Modification of ketonblack carbon support with thiophenic-S followed by loading of Pt_3Co alloy nanoparticles	Ketjenblack (S-KB), modified with thiophene-S, improved proton and O_2 transport by homogenizing the ionomer distribution; The Pt_3Co/S-KB catalyst demonstrated high PEMFC performance at low Pt loading and exceeded the U.S. Department of Energy (DOE) nominal power and Pt utilization targets.	Zhang et al., 2025
Pt/HCCP (P-doped high crystalline carbon supported Pt)	P	Phosphorus-doped high crystalline carbon (HCCP)	Doping of highly crystalline carbon with P via spin-on doping (SOD) method followed by loading of Pt nanoparticles.	Pt/HCC_P (P-doped high crystalline carbon supported Pt) achieved a maximum power density of 0.98 W cm^{-2}; After 20,000 ADT cycles, the power density decreased by only 7.6%, while the loss in Pt/LCC was 58.7%. P addition significantly increased the strength of PEMFC by improving the dispersion and anchoring of Pt nanoparticles.	Kim et al., 2026
Pt_2CuFe/MHC (MHC: carbon with multiple heteroatoms)	N, S	Carbon with multiple heteroatoms (MHC)	Formation of Pt_2CuFe intermetallic structure on multi-heteroatom doped carbon support by immersion-pyrolysis-reduction	Pt_2CuFe/MHC reached a mass activity of 2.07 A $mgPt^{-1}$ at 0.9 V; In MEA tests, it showed peak power densities of 1.29 and 3.14 W cm^{-2} under H_2-air and H_2-O_2 conditions, respectively, and retained 85.3% of its activity after 30,000 cycles.	Lu et al., 2026

4. CONCLUSIONS AND RECOMMENDATIONS

Heteroatom-doped carbon-supported structures offer a significant material design approach for improving the strength and activity of Pt-based PEMFC electrocatalysts. Literature studies indicate that the effect of heteroatoms such as N, S, and P cannot be explained solely by the total doping amount. The synthesis methods and heteroatom types used can alter the surface properties of the carbon support, the ionomer distribution in the catalyst layer, and the metal-support interaction. These changes can affect the stability of the catalyst and its ORR performance (Hornberger et al., 2022; Kim et al., 2026; Ott et al., 2022; Shen et al., 2023; Zhang et al., 2025). Therefore, the effect of heteroatom doping needs to be evaluated together with the electrochemical and structural properties of the catalyst.

The combined use of bimetallic systems such as PtFe, PtCo, PtNi, and PtCu with heteroatom-doped carbon supports yields remarkable results in terms of regulating the metal-support interface (Huang et al., 2022; Niu et al., 2024; Xue et al., 2024; Yan et al., 2023; Zhang et al., 2023). Furthermore, when heteroatom addition and alloying or intermetallic structure change together within the same system,

attributing the observed performance improvement solely to heteroatom addition cannot be considered appropriate.

Future studies will require comparative experimental designs that can evaluate the effects of heteroatom amount and type as independently as possible from metal particle size, alloy composition, and the structural properties of the carbon support. Furthermore, it should be considered that the analysis and characterization results may not fully reflect the catalyst structure of PEMFCs under actual operating conditions. For these reasons, investigating the interactions between catalyst components under real operating conditions is important for a more accurate understanding of the mechanisms that determine performance.

Catalyst development studies should not focus solely on the high initial ORR activity obtained under rotating disk electrode (RDE) conditions. The effect of heteroatom doping on PEMFC performance should be determined by evaluating long-term durability, low Pt loading, proton and oxygen transport, and MEA performance as a whole. In this context, ionomer distribution in the catalyst layer and accessibility of active sites are also important factors determining cell performance. The primary goal in the future development of heteroatom-doped Pt-based catalysts should be to create systems that simultaneously provide high ORR activity, low Pt loading, high stability, and suitable catalyst layer properties.

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SYNTHESIS OF HCL-DOPED POLYANILINE BY CHEMICAL OXIDATIVE POLYMERISATION AND ITS ADSORPTIVE PERFORMANCE FOR METHYLENE BLUE

HCL İLE DOPLANMIŞ POLİANİLİNİN KİMYASAL OKSİDATİF POLİMERİZASYONLA SENTEZİ VE METİLEN MAVİSİ İÇİN ADSORPSİYON PERFORMANSI

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ÖZET

Polianilin (PANI), oda sıcaklığında amonyum persülfatın oksidan olarak kullanıldığı 1 M hidroklorik asit ortamında anilinin kimyasal oksidatif polimerizasyonu yoluyla sentezlendi; bu işlem sonucunda polimerin iletken emeraldin tuzu formu koyu renkli bir toz halinde elde edildi. HCl ile doplanmış PANI daha sonra sulu çözeltiden katyonik boya metilen mavisi (MB^+) için bir adsorban olarak değerlendirildi. Sabit MB^+ konsantrasyonu (100 ppm) koşulunda, başlangıç çözeltisinin pH'ının etkisi 2-10 aralığında incelendi ve en yüksek adsorpsiyon pH 3'te elde edildi. Ardından, bu pH değerinde, 0,1 g/10 mL adsorban dozu kullanılarak 10-1000 ppm başlangıç konsantrasyon aralığında konsantrasyona bağlı adsorpsiyon incelendi. Deneysel izotermler Langmuir, Freundlich ve Temkin modellerine uygulandı. Üç model için de uyum anlamlı bulundu. Langmuir modeli en iyi açıklamayı sağladı (R^2 = 0,991) ve 1429 L mol^{-1}' lik bir Langmuir sabiti ile 0,07 mol kg^{-1} (≈22 mg g^{-1}) tek tabaka kapasitesi tanımladı. Freundlich heterojenlik parametresi (β = 0,49) ve Temkin enerji faktörü (A_T = 30,82 × 10^3 L mol^{-1}) de hesaplandı. Langmuir ve Temkin sabitlerinden hesaplanan Gibbs serbest enerji değişimleri sırasıyla -17,99 ve -25,61 kJ mol^{-1} olarak bulundu; bu da HCl ile doplanmış PANI üzerinde MB^+ adsorpsiyonunun kendiliğinden gerçekleştiğini gösterdi. Langmuir kinetik yaklaşımıyla yapılan değerlendirme sonucunda $\Theta_{e,theor} - k_1/k_2 < 0$ değeri elde edildi; bu sonuç sürecin birinci dereceden hız davranışını izlediğini gösterdi. Sonuçlar, herhangi bir destek veya kompozit modifikasyonu içermeyen HCl katkılı PANI'nin, katyonik boyaların giderilmesinde etkili bir adsorban olduğunu ortaya koymaktadır.
Anahtar kelimeler: Polianilin, HCl doplama, oksidatif polimerizasyon, metilen mavisi, adsorpsiyon.

ABSTRACT

Polyaniline (PANI) was synthesised by the chemical oxidative polymerisation of aniline in 1 M hydrochloric acid medium using ammonium persulfate as the oxidant at room temperature, yielding the conducting emeraldine salt form of the polymer as a dark powder. The HCl-doped PANI was then evaluated as an adsorbent for the cationic dye methylene blue (MB^+) from aqueous solution. The effect of the initial solution pH was examined over the range 2-10 at a fixed MB^+ concentration of 100 ppm, and the highest uptake was obtained at pH 3. Concentration-dependent adsorption was subsequently studied at this pH over an initial concentration range of 10-1000 ppm at an adsorbent dose of 0.1 g/10 mL. The experimental isotherms were fitted to the Langmuir, Freundlich and Temkin models; agreement was significant for all three, with the Langmuir model providing the best description (R^2 = 0.991) and defining a monolayer capacity of 0.07 mol kg^{-1} (≈22 mg g^{-1}) together with a Langmuir constant of 1429 L mol^{-1}. The Freundlich heterogeneity parameter (β = 0.49) and the Temkin energy factor (A_T = 30.82 × 10^3 L mol^{-1}) were also derived. Gibbs free energy changes calculated from the Langmuir and Temkin constants were -17.99 and -25.61 kJ mol^{-1}, respectively, indicating that MB^+ adsorption on HCl-doped PANI proceeds spontaneously. Assessment by the Langmuir kinetic approach gave $\Theta_{e,theor} - k_1/k_2 < 0$, showing that the process follows first-order rate behaviour. The results demonstrate that HCl-doped PANI, without any support or composite modification, is an effective adsorbent for cationic dye removal.
Keywords: Polyaniline, HCl doping, oxidative polymerisation, methylene blue, adsorption.

1. INTRODUCTION

Rapid industrialisation and urban growth have intensified the discharge of coloured effluents into natural water bodies, and the textile sector is among the largest contributors to this burden (Tripathi et al., 2023). Synthetic dyes are designed to resist fading and consequently resist biodegradation as well; once released, they persist in aquatic systems, reduce light penetration and dissolved oxygen levels, and disturb photosynthesis and the wider aquatic food chain (Hama Aziz et al., 2024; Tripathi et al., 2023). Dye-bearing wastewater must therefore be treated before it reaches receiving water.

Methylene blue (MB^+, $C_{16}H_{18}N_3SCl$) is a cationic thiazine dye first synthesised in 1876 and still one of the most widely used colouring and staining agents in the textile, paper and leather industries (Nguyen et al., 2022). Its strong absorption near 665 nm makes it a convenient model adsorbate, but its environmental profile is far from benign. MB^+ has been described as a potentially carcinogenic pollutant, and exposure has been associated with skin irritation, vomiting, headache, elevated blood pressure and fever (Nguyen et al., 2022); prolonged contact has likewise been linked to nausea and dizziness (Duhan & Kaur, 2020). MB^+ is thus a representative and well-justified target for cationic dye removal studies.

A wide range of technologies have been applied to dye-laden effluents, including coagulation-flocculation, membrane filtration, advanced oxidation, photocatalysis and biological degradation. In practice these routes are frequently limited by incomplete removal, high energy or reagent demand, sludge generation and the formation of secondary by-products (Hama Aziz et al., 2024; Tripathi et al., 2023). Adsorption remains the most widely preferred alternative because it is operationally simple, comparatively inexpensive, adaptable to different effluent compositions, and does not generate toxic degradation intermediates; spent adsorbents can also often be regenerated and reused (Hama Aziz et al., 2024). The efficiency of any adsorption system, however, is governed by surface chemistry and surface charge of the solid phase, which in turn dictate the electrostatic, ion-exchange and complexation contributions to uptake (Mert & Ulusoy, 2024).

Among candidate adsorbents, polyaniline (PANI) has attracted sustained attention. It is prepared straightforwardly by chemical oxidative polymerisation of aniline in acidic medium using ammonium persulfate as oxidant, the monomer is inexpensive, and the resulting polymer shows good environmental and thermal stability (Bednarczyk et al., 2021). PANI exists in three oxidation states, of which the half-oxidised emeraldine is of primary interest: protonation of emeraldine base with a protonic acid converts the insulating polymer into the conducting emeraldine salt, and hydrochloric acid is the most commonly employed dopant for this purpose (Bednarczyk et al., 2021). From an adsorption standpoint, the value of PANI lies in the density and variety of its interaction sites. The backbone carries amine and imine nitrogen atoms alongside aromatic rings, so that electrostatic attraction, π-π stacking and hydrogen bonding can all operate simultaneously (Duhan & Kaur, 2020; Samadi et al., 2021). Critically, the surface charge of PANI is not fixed: it can be tuned through doping and de-doping or through the pH of the medium, which makes protonation state a design variable rather than a fixed property (Samadi et al., 2021).

Several studies have exploited this behaviour for MB^+. Duhan and Kaur (2020) reported 91% MB^+ removal by polyaniline nanofibre base, with data following the Freundlich isotherm and pseudo-second-order kinetics. Djellali et al. (2022) combined DFT calculations with batch experiments on doped and non-doped PANI and concluded that π-π stacking and van der Waals forces dominate, with an adsorption energy of about 14 kJ mol^{-1} indicating a purely physical mechanism. Bensedira et al. (2022) evaluated PANI and PANI/SiO_2 and again found pseudo-second-order kinetics across the temperatures studied. Chloride-doped PANI has also been used as a coating: Mohammad and Atassi (2020) showed that depositing it on electrospun polylactic acid and polyacrylonitrile membranes improved both adsorption performance and reusability relative to the uncoated supports. More recently, Mehennaoui et al. (2026) compared HCl- and H_2SO_4-doped Luffa/PANI composites and found that although the HCl-doped material had the larger BET surface area, the sulfate-doped one adsorbed more MB^+, a direct demonstration that dopant-controlled surface chemistry can outweigh total porosity. The pH sensitivity of these systems is equally well established; Galloni et al. (2022) reported a point of zero charge near 2.87 for PANI-modified adsorbents, below which imine nitrogens are readily protonated and the surface becomes positively charged.

Despite this body of work, most reports concern PANI composites, coatings or the de-doped base form. Systematic adsorption data for plain HCl-doped PANI, the emeraldine salt as directly obtained from synthesis, without any support or secondary component, remain comparatively scarce, particularly when

pH dependence, multi-model isotherm analysis, isotherm-derived thermodynamics and kinetic order assessment are treated together.

The present work addresses this gap. PANI was synthesised by chemical oxidative polymerisation in hydrochloric acid medium and evaluated as an adsorbent for MB. The effect of initial pH was examined over the range 2-10 at a fixed MB concentration of 100 ppm to identify the optimum working pH. Concentration-dependent adsorption was then studied at that pH over 10-1000 ppm, and the experimental isotherms were fitted to the Langmuir, Freundlich and Temkin models. Gibbs free energy changes were calculated from the energy-related constants of the Langmuir (K_L) and Temkin (A_T) models, and the reaction order was assessed using the Langmuir kinetic approach with parameters derived from the isotherm analysis.

2. MATRIALS AND METHOD

2.1 Chemicals

Aniline (ACS reagent) was purchased from Sigma-Aldrich and pre-distilled before use. Ammonium persulfate (APS, ACS reagent) and hydrochloric acid (HCl, ACS reagent) were obtained from Sigma-Aldrich and used as received. Methylene blue (MB^+, $C_{16}H_{18}ClN_3S{\cdot}3H_2O$) was supplied by Biomatic. Sodium hydroxide (Kimetsan) and HCl were used for pH adjustment. All solutions were prepared with distilled water.

2.2. Synthesis of HCl-doped PANI

PANI was synthesised at room temperature by chemical oxidative polymerisation. Polymerization was carried out in a 250-ml three-neck pear-shaped reactor. After adding 5 g of aniline to 180 mL of 1 M HCl, the mixture was transferred to the reactor. 12.25 g of APS (APS/aniline molar ratio: 1) was dissolved in 20 mL of 1 M HCl and then added to the reaction mixture via a dropping funnel over a period of 20 minutes. Due to the exothermic reaction occurring during the addition, the cooling jacket surrounding the reactor was cooled, and the reaction continued at 25°C for 24 hours using a magnetic stirrer at 500 rpm. The reactor was then drained, and the resulting PANI was filtered through filter paper and washed with distilled water. After washing, the PANI was dried in an oven at 40°C for 1 day; upon weighing, the reaction yield was calculated to be 100.5 ± 0.5%. The resulting dark powder, corresponding to the chloride-doped emeraldine salt form of PANI, was ground and stored in a closed container for use as adsorbent. No de-doping step was applied, so that the polymer was retained in its protonated, HCl-doped state throughout.

2.3. Characterisation

The molecular structure of the synthesised polymer was examined by Fourier transform infrared spectroscopy (FTIR) between 4000 and 500 cm^{-1}. Samples were mixed with an appropriate amount of KBr and compressed into pellets prior to measurement. The spectra were inspected for the characteristic benzenoid and quinonoid ring-stretching bands of PANI, for the C-Cl stretching vibration arising from the dopant anion, and for the broad electronic band associated with charge delocalisation along the protonated backbone, all of which serve as evidence for successful chloride doping.

2.4. Adsorption experiments

All adsorption studies were carried out in batch mode at room temperature using an adsorbent dose of 0.1 g per 10 mL of solution, with a contact time of 24 h and intermittent stirring. Equilibrium MB^+ concentrations were determined spectrophotometrically by recording the absorbance of the equilibrium solutions at 665 nm against a distilled water blank, and concentrations were calculated from a calibration curve prepared from MB^+ standards.

2.4.1. Effect of pH

The influence of the initial solution pH on MB^+ uptake was investigated over the range pH 2-10 at a constant initial dye concentration of 100 ppm. The pH of each solution was adjusted with 0.1 M HCl and/or 0.1 M NaOH before contact with the adsorbent.

2.4.2. Effect of concentration (isotherms)

Concentration-dependent adsorption was studied at the pH giving maximum uptake (pH 3) using initial MB^+ concentrations between 10 and 1000 ppm. The adsorbed amounts, Q (mol kg^{-1}), were calculated from Eq. (1);

$$Q = \left[\frac{C_i - C_e}{m}\right] V \quad (1)$$

where; Q (mol kg^{-1}) amount of adsorbed substance, C_i and C_e (mol L^{-1}) initial and equilibrium concentrations of the adsorbed species, m (kg) mass of the adsorbent and V (L) solution volume.

2.4.3. Evaluation of the data

The experimental isotherms obtained were evaluated using the Langmuir, Freundlich, and Temkin models. The Langmuir model is given by Eq. (2), where "X_L" represents the adsorption capacity (Langmuir monolayer capacity) and "K_L" represents the Langmuir constant related to the adsorption energy (L mol^{-1}).

$$Q = \frac{K_L X_L C_e}{1 + K_L C_e} \quad (2)$$

The Freundlich adsorption model, Eq. (3), is related to X_F, which is associated with capacity, and β ($0 < \beta < 1$), defined as the heterogeneity of the adsorbent surface. According to the Freundlich model, a small β value indicates a more heterogeneous adsorbent surface.

$$Q = X_F C_d^{\beta} \quad (3)$$

The Temkin model, Eq. (4), includes the "A_T" factor related to adsorption energy, which takes into account the interaction between the adsorbent and the adsorbate; according to the model, the heat of adsorption possessed by the molecules decreases linearly with adsorption as a result of adsorbate-adsorbate interactions in the adsorption layer (on the surface). "b" in the model is the Temkin isotherm constant.

$$Q = \frac{RT}{b} \ln(A_T C_e) \quad (4)$$

Gibbs free energy changes were derived from the energy-related constants of the two applicable models, using for the Langmuir isotherm Eq. (5), and for the Temkin isotherm Eq. (6).

$$\Delta G = -RT \ln K_L \quad (5)$$
$$\Delta G = -RT \ln A_T \quad (6)$$

The Langmuir kinetic model is a theoretical model developed using a differential equation that includes first- and second-order rate terms; the Langmuir adsorption parameters were used in the modeling. Experimental $\Theta_{e,d}$ loading rate is found using the Eq. (7)

$$\Theta_e = \frac{C_0 - C_e}{X_L D} \quad (7)$$

where 'C_0' ve 'C_e' initial and equilibrium concentrations, 'X_L' maximum adsorbent capacity, 'D' indicates the adsorbent dose.

The theoretical filling ratio, $\Theta_{e,k}$, is determined using Eq. (8).

$$\Theta_{e,k} = \frac{K_L(X_L D + C_0) + 1 - \sqrt{K_L^2 (C_0 - X_L D)^2 + 2K_L(C_0 + X_L D) + 1}}{2K_L X_L D} \quad (8)$$

where "K_L" is the adsorption distribution coefficient determined from the Langmuir model.

The ratio of the rate constants in the Langmuir kinetic model is determined using Eq. (9).

$$\frac{k_1}{k_2} = \frac{\sqrt{K_L^2 (C_0 - X_L D)^2 + 2K_L(C_0 + X_L D) + 1}}{K_L X_L D} \quad (9)$$

Adsorption kinetics are first-order when $k_1/k_2 \geq \theta_e$, second-order only when $k_1/k_2 << \theta_e$, and hybrid (first- and second-order) when $k_1/k_2 < \theta_e$.

3. RESULTS and DISCUSSION

3.1. Characterization

The reaction mechanism for the product obtained by the oxidation of aniline with ammonium persulfate in a 1 M HCl medium is shown in Figure 1. Chemical oxidative polymerization carried out in a strongly acidic medium leads to the formation of linear chains, with aniline units primarily linked in the para position. During polymerization, protons present in the medium protonate the imine nitrogens, creating polaron centers along the chain, and Cl^- ions are incorporated into the structure as counterions that balance these positive centers. The resulting dark-colored powder therefore corresponds to the conductive emeraldine salt form rather than the insulating emeraldine base. The calculation of the reaction yield as 100.5 ± 0.5%, based on the aniline mass, also indirectly supports this finding. Since the contribution of the Cl^- counterion is added to the product mass, it is an expected result that the apparent yield for doped PANI exceeds 100%.

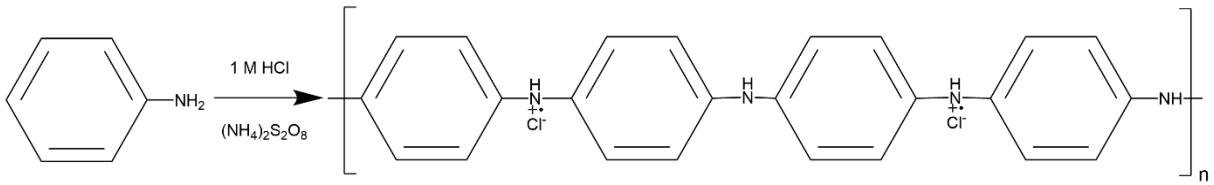


Figure 1. HCl doped Polyaniline Synthesis

The molecular structure of the synthesized polymer was examined using FTIR spectroscopy, and the spectrum is presented in Figure 2. The broad band around 3450 cm^{-1} corresponds to the N–H stretching vibration overlapping with the O–H stretching vibration of moisture trapped in the structure, while the weak band at 3025 cm^{-1} originates from the aromatic C–H stretching vibration. The intense bands at 1580 and 1490 cm^{-1} correspond to the quinoid (Q) and benzenoid (B) ring stretching vibrations, respectively.

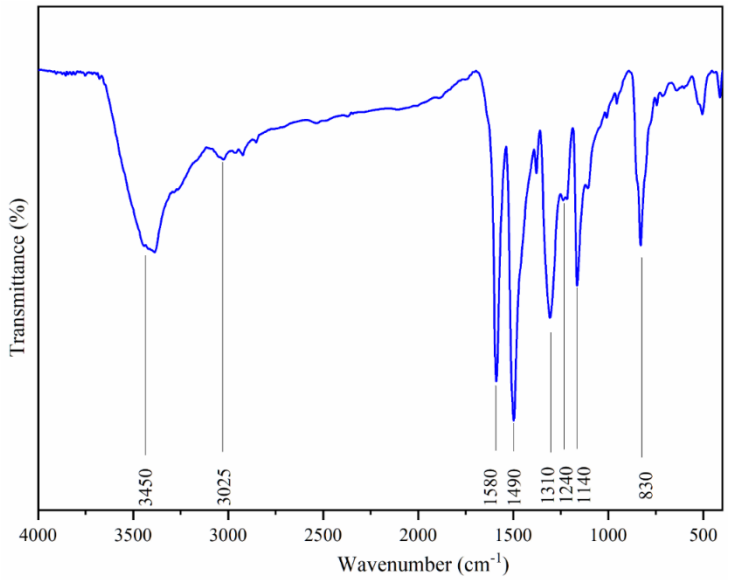


Figure 2. FTIR spectrum of HCl doped PANI

The most direct evidence of doping comes from the bands at 1310, 1240, and 1140 cm^{-1}(Tang et al., 1988; Trchová & Stejskal, 2011). While the band at 1310 cm^{-1} is associated with π-electron delocalization induced by protonation, the band at 1240 cm^{-1} corresponds to the C–N^+• stretching vibration in the polaron structure and is considered the characteristic band of the conductive protonated form. The broad and intense band observed at 1140 cm^{-1} belongs to the –NH^+= vibrational mode of charged units of the form Q=NH^+–B or B–NH^+•–B. The intensity of this band increases with the degree

of protonation and is evaluated as a measure of the presence of positive charges along the chain. The observation of these three bands at distinct intensities indicates that Cl^- doping was successfully achieved and that the polymer is at a high level of protonation. The band at 830 cm^{-1} originates from the out-of-plane C–H bending vibration of two adjacent hydrogen atoms in the 1,4-disubstituted benzene ring and confirms that para bonding predominates along the chain(Trchová & Stejskal, 2011). The FTIR findings confirm that the form of the synthesized material used in the adsorption experiments is emeraldin salt.

3.2. Adsorptive features of HCl-doped PANI for MB^+ adsorption

3.2.1. Adsorption dependence on pH

The effect of initial pH on MB^+ adsorption was investigated in the pH range of 2–10 at a dye concentration of 100 ppm, and the results are presented in Figure 3.

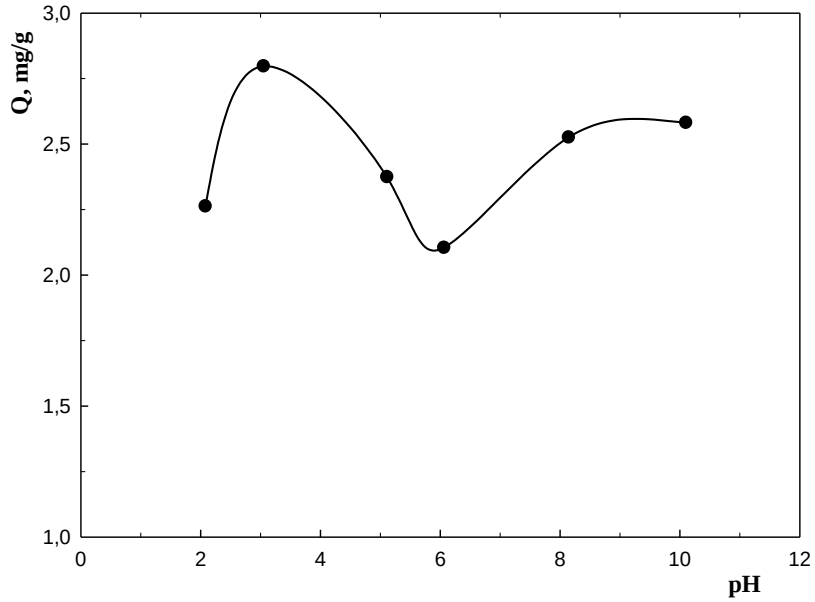


Figure 3. The effect of pH on MB^+ adsorption

The adsorbed amount varied between 2.10 and 2.80 mg g^{-1} across the entire range. This narrow range indicates that pH is not the sole determining factor in the system under study and, consequently, that adsorption is not predominantly electrostatic in nature. Djellali et al. (2022) reported that the binding of MB^+ to PANI is governed by π–π stacking and van der Waals forces, with an interaction energy of approximately 14 kJ mol^{-1}. These interactions between the aromatic backbone and the phenothiazine ring of the dye are relatively independent of the ambient pH, and the limited variation observed is consistent with this mechanism.

However, the curve is not monotonic; a maximum (2.80 mg g^{-1}) is observed at pH 3, a minimum (2.10 mg g^{-1}) at pH 6, and a second increase (2.53–2.59 mg g^{-1}) in the pH 8-10 range. This two-region behavior can be explained by changes in the adsorbent's protonation state with pH. In the acidic region, the polymer adopts the emeraldine salt form. Under these conditions, where conjugation and chain planarity are at their highest, the accessible surface area for π–π interactions is the widest. The decrease observed at pH 2 can be attributed to the increased H^+ concentration strengthening the repulsion between the protonated surface and the cationic dye, as well as the increase in ionic strength resulting from acid addition, which creates charge screening. The minimum around pH 6 corresponds to a transition region where partial de-doping begins, the surface charge is largely neutralized, and, conversely, free imine/amine regions have not yet formed.

The subsequent increase in the alkaline region is explained by the conversion of the emeraldin salt to emeraldine base. The unpaired electron pairs of the imine and amine nitrogens released as a result of de-doping become capable of forming hydrogen bonds. The surface acquires a net negative charge, making it electrostatically attractive to the cationic MB^+ (Galloni et al., 2022; Samadi et al., 2021). This

observation is consistent with the findings of Djellali et al. (2022), who found alkaline conditions to be superior to acidic conditions.
Isotherm studies were conducted at pH 3, where both the highest adsorption was achieved and the adsorbent retained its emeraldine salt identity.

3.2.2. The adsorption isotherms

The experimental isotherm obtained at pH 3 over an initial concentration range of 10–1000 ppm and its agreement with the models are shown in Figures 4–6, and the calculated parameters are presented in Table 1.

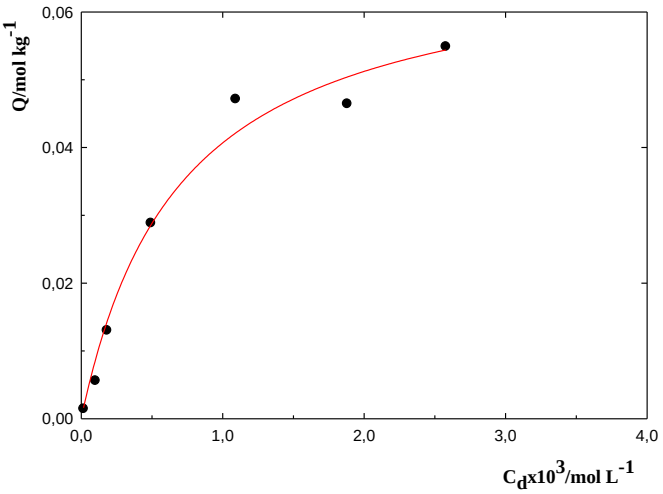


Figure 4. Compatibility of the experimentally obtained MB^+ adsorption isotherms to Langmuir model {$[MB^+]0$=10-1000 ppm, D =0.1 g/10 mL}

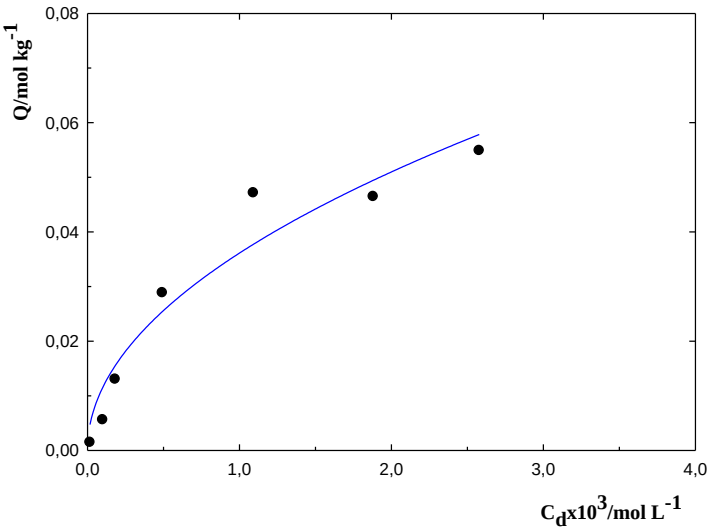


Figure 5. Compatibility of the experimentally obtained MB^+ adsorption isotherms to Freundlich model

{$[MB^+]_0$=10-1000 ppm, D =0.1 g/10 mL}

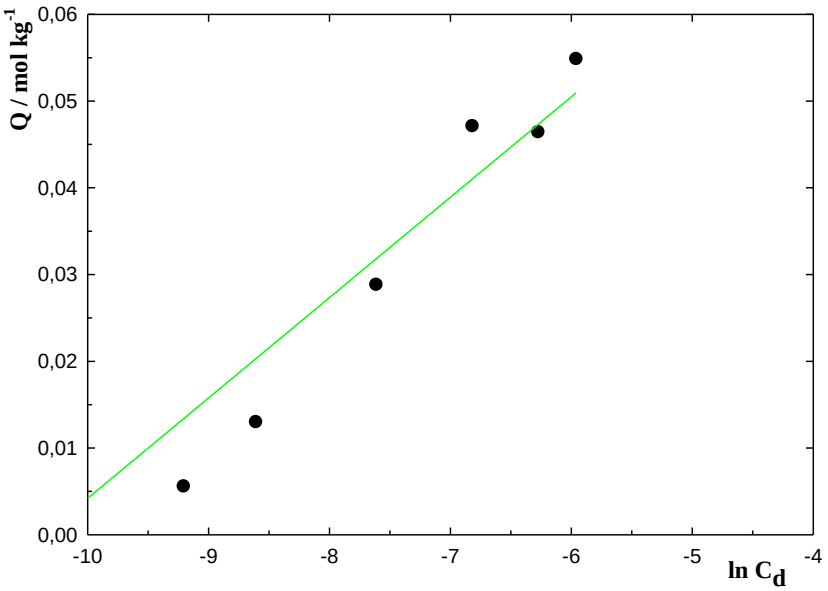


Figure 6. Compatibility of the experimentally obtained MB^+ adsorption isotherms to Temkin model {[MB^+]0=10-1000 ppm, D =0.1 g/10 mL}

Table 1. Langmuir, Freundlich, and Temkin parameters for adsorption of MB^+ onto HCl doped PANI

Langmuir		Freundlich		Temkin	
X_L/molkg^{-1}	0.07	X_F	1.12	A_T/Lmol^{-1}x10^{-3}	30.82
K_L/Lmol^{-1}	1429	β	0.49		
R^2	0.991	R^2	0.970	R^2	0.955

The experimental isotherm exhibits a Type-I (Giles L-type) character, showing a steep increase at low equilibrium concentrations followed by a plateau. This behavior indicates that MB^+ has a high affinity for the adsorbent surface (Thommes et al., 2015). The fit was found to be statistically significant for all three models. The Langmuir model provided the best fit (R^2 = 0.991; Freundlich 0.970; Temkin 0.955). From the Langmuir model, the monolayer capacity X_L was calculated as 0.07 mol kg^{-1} (≈22 mg g^{-1}) and the constant related to the adsorption energy, K_L, as 1429 L mol^{-1}. The high K_L value indicates a strong adsorbent-adsorbate interaction and that the surface is effectively filled even at low concentrations. The superiority of the Langmuir model suggests that adsorption occurs as a monolayer in a limited number of regions that are energetically close to one another.

The β value of 0.49 obtained from the Freundlich model falls within the range $0 < \beta < 1$. This value indicates that adsorption is thermodynamically favorable. The fact that β is significantly less than 1, however, suggests the presence of a certain degree of heterogeneity on the surface. When considered alongside the better fit provided by the Langmuir model, this situation can be interpreted as indicating the presence of a dominant single binding site type (protonated nitrogen centers and adjacent aromatic rings) alongside sites with different energies whose contribution remains secondary. The fact that the Temkin model provides the poorest fit indicates that the interactions between the adsorbed MB^+ molecules and the resulting linear decrease in the adsorption enthalpy are not the primary factors governing the process.

The Gibbs free energy changes calculated from the model constants related to the adsorption energy are presented in Table 2.

Table 2. Thermodynamic parameters related to MB^+ adsorption

Langmuir isotherm 'K_L'		**Temkin isotherm 'A_T'**	
(ΔG=-RTlnK_L)/kJmol^{-1}	-17.99	ΔG/kJmol^{-1}	-25.61

A value of $\Delta G = -17.99$ kJ mol^{-1} was obtained from the Langmuir constant, and $\Delta G = -25.61$ kJ mol^{-1} from the Temkin constant. The difference between the two values stems from the different energy definitions used by the models. While K_L is an adsorption equilibrium constant, A_T is the Temkin binding factor, which incorporates the adsorbent-adsorbate interaction. The fact that both values are negative indicates that the adsorption occurs spontaneously. The fact that their absolute values remain below 40 kJ mol^{-1} suggests that the process proceeds primarily through physical interactions and ion exchange rather than chemical bond formation. This result is consistent with that reported by Djellali et al. (2022), who reported an interaction energy of approximately 14 kJ mol^{-1} for MB^+ adsorption on PANI and attributed the mechanism to π–π stacking and van der Waals forces.

The kinetic order was evaluated using the approach of Liu and Shen (2008) based on Langmuir isotherm parameters, and the results are presented in Table 3.

Table 3. Adsorption kinetics parameters derived from the Langmuir kinetic model for MB^+ adsorption onto HCl doped PANI
{$[MB^+]_0$=1.560x10^{-3} mol L^{-1}, D=0.01 kg L^{-1}

Material	**C_ex10^4**	**$\Theta_{e,exp}$**	**$\Theta_{e,theor}$**	**(k_1/k_2)**	**k_1/k_2 - $\Theta_{e,theor}$**		**Langmuir model**
HCl doped PANI		10.90	0.672	0.617	2.994	>0	first-order

At an initial concentration of 500 ppm, the experimental surface occupancy $\Theta_{e,d}$ was found to be 0.672, while the theoretical occupancy $\Theta_{e,k}$ calculated from the model was 0.617. The closeness of these two values indicates that the Langmuir parameters consistently represent experimental behavior. The rate constant ratio $k_1/k_2 = 2.994$, which is greater than the $\Theta_{e,k}$ value. This condition indicates that the Langmuir kinetics have been reduced to a first-order rate equation, implying that the adsorption exhibits first-order kinetics.
The results obtained in this study demonstrate that HCl-doped PANI, without any support or modification, functions as a standalone adsorbent for the removal of cationic dyes.

4. CONCLUSIONS

In this study, polyaniline was synthesized via chemical oxidative polymerization with ammonium persulfate in a 1 M HCl solution and evaluated as an adsorbent for the cationic dye methylene blue directly in the form of emeraldine salt, without undergoing a de-doping process. FTIR analysis confirmed that the synthesized material exists in the form of a conductive salt with a high degree of protonation, as evidenced by the quinone/benzene bands at 1580/1490 cm^{-1}, polaron-derived bands at 1310, 1240, and 1140 cm^{-1}, and the absence of the emeraldine base band at 1378 cm^{-1}.
The pH dependence of adsorption exhibited a two-region behavior. The fact that the adsorbed amount varied only between 2.10 and 2.80 mg g^{-1} in the pH range of 2-10 indicated that the process was not predominantly electrostatic in origin. While π–π interactions were determined to be the decisive factor for the maximum adsorption of emeraldine salt in the acidic region (pH 3; 2.80 mg g^{-1}) under conditions where the salt was preserved, the second peak in the alkaline region was attributed to the surface becoming electrostatically favorable for cationic dyes as a result of partial de-doping.
The isotherms obtained at pH 3 are of Type-I (Giles L-type) character and showed a good fit with all three models, with the Langmuir model providing the best fit ($R^2 = 0.991$). The monolayer capacity was determined to be 0.07 mol kg^{-1} (≈22 mg g^{-1}), and the Langmuir constant was found to be 1429 L mol^{-1}. The free energy changes calculated from the Langmuir and Temkin constants (-17.99 and -25.61 kJ mol^{-1}) indicate that adsorption occurs spontaneously, while the fact that the absolute values remain below 40

kJ mol^{-1} suggests that the process proceeds via physical interactions and ion exchange. Using the Liu and Shen approach, the fulfillment of the condition $k_1/k_2 = 2.994 > \Theta_{e,k} = 0.617$ revealed that the kinetics were reduced to a first-order rate equation.

The findings demonstrate that HCl-doped PANI, which contains no support material or composite modification, functions as a standalone adsorbent for the removal of cationic dyes. To translate these findings into practical applications, the characterization of surface area and morphology, the determination of enthalpy and entropy changes at different temperatures, and the assessment of reusability performance are issues that must be addressed in subsequent stages.

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OXIDE-BASED SOLID ELECTROLYTES FOR SOLID-STATE LITHIUM BATTERIES: ION TRANSPORT, MATERIAL CLASSES, AND PROCESSING STRATEGIES

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ABSTRACT
The safety risks and limited electrochemical stability of flammable liquid electrolytes remain major barriers to the development of high-energy-density lithium batteries. Oxide-based solid electrolytes offer a promising route toward safer solid-state batteries because of their nonflammability, mechanical rigidity, broad electrochemical stability, and atmospheric tolerance. This study evaluates the lithium-ion transport mechanisms, material classes, processing strategies, and practical limitations of oxide solid electrolytes. Garnet-type LLZO and LLZTO, NASICON-type LATP and LAGP, perovskite-type LLTO, and LISICON-related compositions are comparatively examined. Particular attention is given to the effects of crystal symmetry, aliovalent doping, lithium vacancies, grain-boundary chemistry, and ceramic processing on ionic conductivity. As an experimental case study, Ta-doped $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ was prepared by a conventional solid-state route involving wet ball milling at 350 rpm for 12 h, calcination at 950 °C for 12 h, uniaxial pressing at 300 MPa, and sintering at 1175 °C for 6 h. X-ray diffraction revealed progressive phase evolution from the precursor mixture toward a predominantly garnet-type LLZTO structure. The principal garnet-related reflections were retained after final sintering, while minor additional reflections indicated possible secondary phases. Although the pattern was consistent with Ta-stabilized cubic LLZTO, definitive structural confirmation requires reference-pattern matching and Rietveld refinement. Overall, the findings demonstrate that the performance of oxide solid electrolytes depends on the combined optimization of crystal chemistry, thermal processing, microstructure, and electrode–electrolyte interfaces.
Keywords: Solid-State Batteries; Oxide Solid Electrolytes; LLZO; LLZTO; Li-ion Transport; Composite Electrolytes

1. INTRODUCTION
Lithium-ion batteries (LIBs) have become the leading energy-storage technology for electric vehicles because they contribute to lower CO_2 emissions, improved energy efficiency, and reliable rechargeable operation. Their use is not limited to transportation; LIBs are also extensively employed in portable electronic devices, stationary grid-storage systems, and numerous other applications. Their widespread adoption is associated with several advantageous characteristics, including high specific power, low self-discharge, operation over a relatively broad temperature range, absence of a pronounced memory effect, long cycle life, and comparatively favorable environmental performance. Nevertheless, commercially available LIBs continue to face important challenges concerning safety and achievable energy density. Conventional LIBs generally employ liquid electrolytes containing organic solvents that provide high ionic conductivity. However, the volatility, flammability, and toxicity of these solvents create substantial safety and environmental concerns. Electrolyte leakage, internal short circuits, fire, explosion, and uncontrolled lithium-dendrite formation are among the potential failure mechanisms that may threaten both human health and environmental safety (Bakar et al., 2023)
The energy density attainable with present-day LIB technology remains insufficient for some emerging applications. State-of-the-art systems typically deliver gravimetric energy densities of approximately

210–235 Wh kg^{-1} and volumetric energy densities of about 400–630 Wh L^{-1}. Therefore, the broader electrification of next-generation transportation, portable electronics, and large-scale energy-storage systems will require substantial improvements in both gravimetric and volumetric energy density (Liu and Li 2022, Bills et al. 2020). To address these limitations, considerable research has focused on developing advanced materials for the principal components of LIBs, including anodes, cathodes, and electrolytes (Wieczorek et al. 1989).

Among the proposed strategies, replacing conventional liquid or gel electrolytes with solid ion-conducting materials is considered one of the most promising approaches. Solid-state batteries (SSBs) can provide higher energy density, improved thermomechanical and electrochemical stability, and lower flammability than conventional LIBs, thereby enabling safer, more robust, and more compact energy-storage systems. Their cell architecture also differs fundamentally from that of liquid-electrolyte batteries. In an SSB, the solid electrolyte simultaneously conducts lithium ions between the electrodes and physically separates the cathode from the anode. Consequently, it can perform the functions of both the electrolyte and the separator, eliminating the need for the additional porous separator typically used in conventional LIBs (Bates et al. 2022).

Solid electrolytes are commonly grouped into sulfides, oxides, polymers and composites. Sulfide conductors can reach room-temperature ionic conductivities comparable to liquid electrolytes and are readily densified by pressure, yet many are sensitive to moisture and can release H_2S. Polymer electrolytes offer flexibility and excellent interfacial conformity but often show limited room-temperature conductivity and reduced mechanical strength at temperatures where segmental motion becomes rapid. Oxide electrolytes are nonflammable and usually more stable in air and at elevated temperature. Their main disadvantages are brittleness, high processing temperatures, difficult solid-solid contact, and large interfacial resistance (Biçer et al. 2025). The principal differences among oxide-, sulfide-, and polymer-based solid electrolytes in terms of ionic conductivity, air stability, mechanical properties, interfacial contact, processing requirements, moisture sensitivity, lithium-metal compatibility, and manufacturing scalability are summarized in Table 1.

Table 1. Comparison of oxide, sulfide, and polymer solid electrolytes

Property	**Oxide**	**Sulfide**	**Polymer**
Ionic conductivity	High	Very high	Moderate
Air stability	High	Low	High
Mechanical strength	High	Moderate	Low
Interfacial contact	Difficult	Excellent	Excellent
Processing temperature	High	Low	Low
Moisture sensitivity	Low	High	Low
Li-metal compatibility	Variable	Variable	Variable
Manufacturing scalability	Challenging	Promising	Promising

In oxide-based solid electrolytes, macroscopic ionic conductivity is governed by the combined effects of crystal structure, defect chemistry, phase purity, grain-boundary properties, and ceramic microstructure. Processing conditions are therefore as important as chemical composition because calcination, sintering, and densification directly influence the continuity of Li^+-transport pathways and the overall resistance of the electrolyte (Famprikis et al. 2019).

In addition to bulk and grain-boundary transport, the electrochemical performance of oxide solid electrolytes is strongly governed by their contact with the electrodes. As illustrated in Figure 1, solid

electrolyte–electrode interfaces may undergo parasitic redox, chemical, and electrochemical reactions, resulting in the formation of resistive interphases that obstruct Li^+ transport. This issue is particularly important for oxide electrolytes because their rigid ceramic nature can produce limited solid–solid contact and high interfacial resistance, despite their generally favorable thermal and chemical stability. Achieving stable battery operation therefore requires chemically compatible electrode–electrolyte combinations, kinetically stabilized interfaces, or artificial protective interlayers that suppress undesirable reactions while preserving continuous Li^+-transport pathways. Accordingly, the practical performance of oxide solid electrolytes must be evaluated through the combined consideration of crystal structure, defect chemistry, ceramic processing, microstructure, and interfacial engineering.

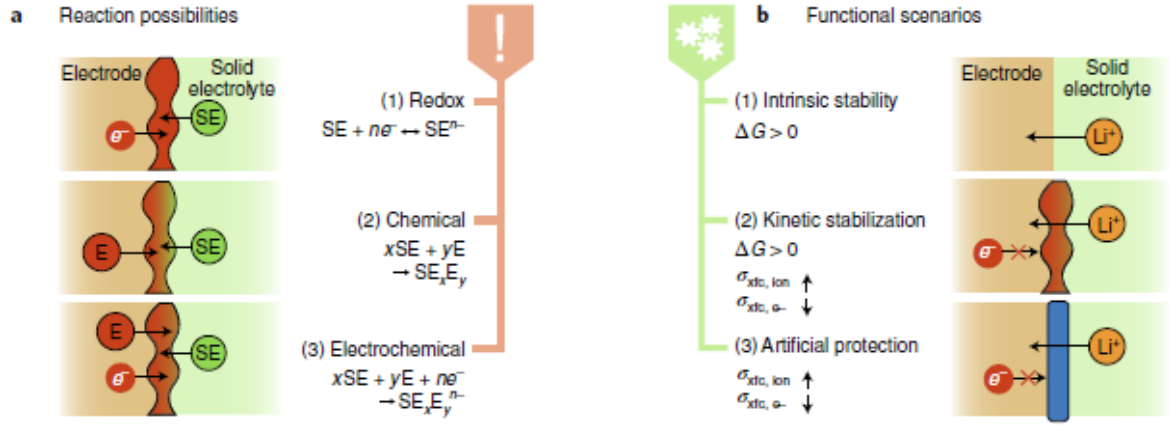


Figure 1. Possible reaction pathways and stabilization strategies at solid electrolyte–electrode interfaces**.** (a) Parasitic redox, chemical, and electrochemical reactions that may occur at the solid electrolyte–electrode interface depending on the thermodynamic driving force. (b) Interface-engineering strategies based on intrinsic compatibility, kinetic stabilization, and artificial protective interlayers. An effective interface should enable continuous Li^+ transport while suppressing electron transfer and the interdiffusion of chemical species. SE and E represent species in the solid electrolyte and electrode, respectively (Famprikis et al. 2019).

This review provides a systematic evaluation of oxide-based solid electrolytes by integrating three closely related aspects: lithium-ion transport mechanisms, structural classifications, and materials-processing strategies. The crystal chemistry, defect structure, ionic-conduction pathways, and principal limitations of garnet-, NASICON-, perovskite-, and LISICON-type electrolytes are comparatively assessed, with particular emphasis on LLZO and Ta-substituted LLZTO. The review further examines how phase composition, dopant chemistry, grain-boundary characteristics, densification, and electrode–electrolyte interfaces collectively determine the measured ionic conductivity and cell-level electrochemical performance. By establishing relationships among composition, processing, structure, and functionality, this study aims to identify the critical parameters required to translate the favorable intrinsic properties of oxide electrolyte powders into dense, low-resistance, and operationally stable solid-state battery architectures.

1.1. Fundamentals of solid-state oxide electrolytes

1.1.1. Ionic Transport Mechanisms

Lithium-ion transport in crystalline oxide electrolytes occurs through thermally activated hopping between energetically accessible crystallographic sites. Ionic conductivity depends on the concentration and mobility of charge carriers, the availability of vacant sites, the connectivity of migration pathways, and the dimensions of structural bottlenecks. Although vacancies can facilitate Li^+ migration, excessive defect concentrations may promote defect association, local ordering, or lattice distortion and thereby increase the migration barrier (Geiger et al. 2011).

Lithium-ion transport must be evaluated across multiple length scales. As illustrated in Figure 2, atomic-scale hopping determines the intrinsic mobility of Li^+ ions, whereas crystalline and amorphous regions, grain boundaries, porosity, and secondary phases control transport at the microstructural scale. At the device level, electrode–electrolyte contact and charge-transfer resistance contribute to the overall cell

impedance. Consequently, high intrinsic ionic conductivity within individual grains does not necessarily ensure low total resistance or satisfactory electrochemical performance in a complete cell (Famprikis et al. 2019).

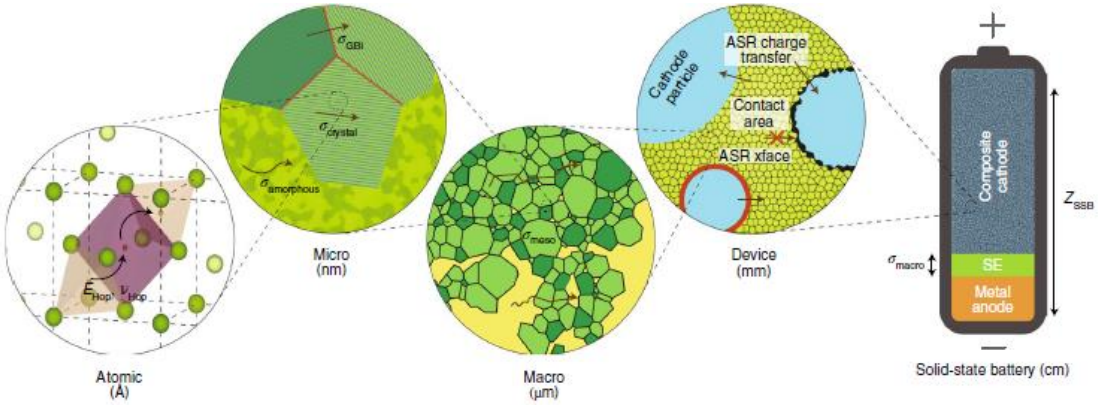


Figure 2. Multiscale lithium-ion transport in solid electrolytes. Li^+ transport extends from atomic-scale hopping to transport through crystalline and amorphous regions, grain boundaries, and macroscopic microstructures. At the device scale, electrode–electrolyte contact and charge-transfer processes collectively determine the overall impedance of the solid-state battery (Famprikis et al. 2019).

1.1.2. Crystal Structure and Lithium-Ion Migration

The crystal structure of oxide solid electrolytes determines the dimensionality and connectivity of Li^+-migration pathways. Garnet electrolytes contain three-dimensional networks of tetrahedral and octahedral Li sites, whereas NASICON, perovskite, and LISICON-type structures enable ion transport through interconnected channels, vacant crystallographic sites, or open tetrahedral frameworks. Three-dimensional pathways are generally less susceptible to local blocking because they provide alternative routes for Li^+ migration.

Crystal symmetry and Li-site occupancy also strongly influence ionic conductivity. In LLZO, the tetragonal phase contains an ordered Li sublattice that restricts ion mobility, while the cubic phase exhibits partially occupied and disordered Li sites, enabling more isotropic and rapid transport. Cubic and tetragonal LLZO are commonly assigned to the Ia–3d and $I4_1/acd$ space groups, respectively. Because peak overlap and secondary phases can complicate XRD interpretation, reliable phase identification should combine structural refinement with complementary techniques such as Raman spectroscopy or solid-state NMR (Umair et al. 2025).

1.1.3. Defects, Vacancies, and Grain Boundaries

Point defects regulate the concentration of mobile Li^+ carriers, whereas grain boundaries and porosity determine whether these ions can move effectively across the entire electrolyte. Aliovalent doping can enhance conductivity by generating Li vacancies; however, dopant segregation, lithium volatilization during sintering, and secondary-phase formation may produce resistive regions at grain boundaries.

Grain-boundary transport is governed by local composition, space-charge effects, defect distribution, and interfacial structure. Lithium-depleted or secondary-phase-rich boundaries can obstruct ion migration, whereas vacancy-rich boundaries without substantial lithium depletion may facilitate transport. Porosity further reduces the number of effective conduction pathways, decreases electrode–electrolyte contact, and may promote lithium-filament penetration. Although densification generally improves total ionic conductivity, excessive sintering can cause abnormal grain growth, pore entrapment, lithium loss, and mechanical degradation. Therefore, defect chemistry, grain-boundary composition, relative density, and mechanical integrity must be optimized together (Gregori et al. 2017; Cheng et al. 2015).

1.1.4. Relationship between Crystal Chemistry and Ionic Conductivity

High ionic conductivity requires a continuous migration network, an appropriate concentration of lithium vacancies, and sufficiently low migration barriers. In LLZO, Al^{3+} and Ga^{3+} preferentially occupy lithium sites, whereas Ta^{5+} and Nb^{5+} primarily substitute for Zr^{4+}. These aliovalent substitutions modify lithium content and site occupancy and can contribute to the stabilization of the highly conductive cubic

structure. However, total conductivity also depends on dopant solubility, site preference, segregation, phase purity, grain-boundary composition, and ceramic density. Therefore, cubic symmetry alone does not guarantee high macroscopic ionic conductivity, and crystal chemistry must be evaluated together with microstructure and processing history (Eggestad et al. 2024).

1.2. Classification of oxide solid electrolytes

1.2.1. Garnet-Type Electrolytes

Garnet-type lithium conductors attracted wide attention after fast lithium transport was reported in $Li_7La_3Zr_2O_{12}$. The Zr-based garnet framework offers high thermal stability and practical compatibility with lithium metal compared with Ti- or Ge-containing oxides that are readily reduced. The central challenge is stabilizing the conductive cubic phase while maintaining high density and low impurity content. Undoped LLZO tends to form a tetragonal, lithium-ordered phase at room temperature when contamination and lithium nonstoichiometry are carefully excluded. Al- and Ga-doped LLZO stabilize the cubic structure by substituting for lithium and creating vacancies. Al is technologically convenient because small amounts can enter the material from alumina crucibles, but uncontrolled contamination undermines compositional reproducibility. Ga can yield high conductivity but may segregate or form Li-Ga-O phases depending on loading and thermal history. Zr-site substitution with Ta^{5+} or Nb^{5+} provides another route to vacancy formation. Ta-doped LLZO can be prepared without intentional Al, and Ta substitution lowers the temperature required to stabilize the cubic modification (Umair et al. 2025).

The nominal composition $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ is widely used because Ta^{5+} substitution creates 0.6 lithium vacancies per formula unit relative to $Li_7La_3Zr_2O_{12}$. These vacancies suppress long-range lithium ordering and facilitate access to the cubic garnet network. Nevertheless, Ta content must be interpreted together with lithium excess, crucible interaction, and sintering conditions. Loss of lithium can increase secondary-phase formation, while excessive lithium compensation can leave residual Li_2CO_3 or Li-rich phases. X-ray diffraction, elemental analysis, density measurement, and impedance spectroscopy should therefore be evaluated as a single data set. For battery integration, LLZO and LLZTO offer attractive electronic insulation and stiffness but suffer from poor contact with lithium and composite cathodes. The surface rapidly accumulates Li_2CO_3 and LiOH in ambient air. These species reduce the true area of contact and raise interfacial impedance. Surface cleaning can reduce resistance dramatically by restoring lithium wetting. At higher current density, however, microstructural defects and local electronic conduction can still promote internal lithium deposition. Direct observations and modeling show that pores, cracks, grain boundaries, and nonuniform pressure strongly influence failure (Umair et al. 2025).

1.2.2. NASICON-Type Electrolytes

NASICON-type lithium conductors derive from a rigid phosphate framework that provides interconnected three-dimensional channels. LATP, commonly represented near $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$, and LAGP, commonly represented near $Li_{1.5}Al_{0.5}Ge_{1.5}(PO_4)_3$, are the most studied compositions. Aliovalent substitution of Al^{3+} for Ti^{4+} or Ge^{4+} increases lithium content and modifies site occupancy. Trivalent substitution has been reported to enhance ionic conductivity and sinterability in lithium titanium phosphate systems (Umair et al., 2025).

LATP offers relatively low raw-material cost and good stability in air, but Ti^{4+} can be reduced in direct contact with lithium metal. The resulting mixed ionic-electronic interphase makes direct use against lithium problematic. Protective interlayers or polymer buffers are therefore required. In addition, LATP ceramics frequently contain resistive grain-boundary phases. Additives may improve densification or remove blocking phases, but they can also narrow the electrochemical window or change mechanical properties. Replacing Ti with Ge improves reduction behavior in some operating windows and can provide high bulk conductivity, but Ge increases material cost and remains susceptible to reduction against lithium. LAGP is often processed through a glass-ceramic route, where controlled crystallization produces the NASICON phase. This route offers compositional homogeneity and the possibility of thin sheets, but conductivity depends strongly on crystallization temperature, grain connectivity, residual glass, and secondary phases. The use of LATP or LAGP is therefore most credible when combined with an interface architecture that prevents direct contact with lithium metal (Umair et al. 2025).

1.2.3. Perovskite-Type Electrolytes

Lithium lanthanum titanate, $Li_{3x}La_{2/3-x}TiO_3$, is the reference perovskite oxide electrolyte. Its A sublattice contains Li^+, La^{3+}, and vacancies, while Ti occupies the B site. Lithium migrates through oxygen-square bottlenecks between neighboring A-site cavities. The original report showed bulk conductivity near 10^{-3} S cm^{-1} at room temperature, but much lower total conductivity in polycrystalline samples (Umair et al. 2025). The difference arises largely from grain-boundary blocking.

LLTO illustrates why bulk conductivity alone is an incomplete screening metric. La-rich or Li-depleted grain boundaries create space-charge barriers, and structural ordering can produce anisotropic transport. Processing methods that increase grain size may reduce the number of boundaries but cannot fully remove chemically blocking boundary layers. Furthermore, Ti^{4+} is reduced by lithium metal, which increases electronic conductivity and destabilizes direct contact. LLTO is consequently more suitable as a protected electrolyte, a component in multilayer structures, or a model system for understanding grain-boundary transport than as an unmodified separator against lithium (Umair et al. 2025).

1.2.4. LISICON and Related Oxide Electrolytes

LISICON denotes a family of lithium superionic conductors based on tetrahedral oxide frameworks. Classical compositions derived from Li_4GeO_4-Li_3O_4 or Li_4SiO_4 solid solutions demonstrate how substitution and interstitial lithium can increase carrier concentration. Their advantages include chemical diversity and comparatively open frameworks. However, many oxide LISICON compositions exhibit room-temperature conductivities below those of optimized garnet, NASICON, or perovskite electrolytes, and some contain reducible or expensive elements. Oxynitride derivatives such as LiPON extend the LISICON concept toward amorphous thin films. LiPON has lower conductivity than leading bulk ceramics but offers exceptional uniformity, negligible grain-boundary pathways, and stable cycling in micrometer-scale thin-film batteries. Its success demonstrates that a moderate conductivity can be acceptable when the electrolyte is extremely thin and interfaces are well controlled. This principle also motivates thin-film processing of garnet and NASICON materials (Umair et al. 2025).

2. MATERIALS AND METHODS

2.1. Synthesis and processing of oxide solid electrolytes

2.1.1. Sol-Gel Processing

Sol–gel synthesis enables the homogeneous mixing of precursor species at the molecular level and generally consists of the following stages: dissolution of metal salts or alkoxides, addition of a complexing agent, control of pH and hydrolysis, sol formation, gelation, aging, drying, organic removal, calcination, powder grinding, pelletization, and final sintering. Compared with conventional solid-state reactions, the shorter diffusion distances can reduce the phase-formation temperature and produce finer, more homogeneous powders. The method also facilitates the uniform distribution of dopant elements throughout the structure. However, product quality strongly depends on precursor chemistry, pH, solvent composition, complexing-agent ratio, gelation conditions, and heat-treatment profile. Incomplete organic decomposition may produce carbon residues, whereas rapid combustion can cause agglomeration and chemical inhomogeneity. Furthermore, the high surface area of sol–gel-derived powders increases their sensitivity to moisture, Li^+/H^+ exchange, and surface carbonate formation. Therefore, although sol–gel processing improves precursor homogeneity and reaction kinetics, controlled calcination, densification, and surface handling remain necessary to obtain phase-pure and highly conductive oxide electrolytes (Kokal et al. 2011).

2.1.2. Hot Pressing

Hot pressing applies uniaxial pressure during heating, allowing densification at lower temperature or shorter dwell time than pressureless sintering. The method can suppress pore growth and produce dense garnet pellets. In hot-pressed cubic LLZO, increasing relative density from approximately 85% to 98% increased total ionic conductivity from about 0.0094 to 0.34 mS cm^{-1}, demonstrating the strong effect of connected porosity (Cheng et al. 2015). Pressure-assisted processing can therefore improve both transport and reproducibility. The limitations are equipment cost, restricted geometry, possible anisotropy, die reactions, and low throughput. Spark-plasma sintering and field-assisted techniques shorten thermal exposure further, but carbon contamination, reduction, and nonuniform current distribution must be considered. Pressure-assisted methods are valuable for mechanistic studies and

high-density components, whereas their role in mass production depends on the achievable area, thickness, and cycle time (Kim et al. 2016)

2.1.3. Tape Casting

Tape casting is attractive because it can produce thin, large-area ceramic sheets continuously. A ceramic powder is dispersed in a solvent with dispersant, binder, and plasticizer; the slurry is cast through a doctor blade and dried to form a flexible green tape. After cutting and lamination, binder burnout and sintering produce the dense electrolyte. Thickness reduction directly lowers area-specific resistance, making tape casting more relevant to practical cells than millimeter-scale pellets. LLZO tape casting is chemically demanding. Protic solvents and moisture can promote Li^+/H^+ exchange, while CO^2 exposure produces surface carbonate. Binder burnout must avoid cracking and residual carbon. Thin tapes have a high surface-to-volume ratio and are especially susceptible to lithium loss during sintering. Slurry rheology, drying stress, green density, lithium compensation, and sacrificial powder must therefore be optimized together. Porous-dense bilayers or graded structures can improve electrode infiltration while retaining a dense electronically insulating separator, but they add co-sintering constraints (Jonson et al. 2021).

2.1.4. Thin-Film Deposition

Thin-film deposition minimizes ohmic loss by reducing electrolyte thickness from hundreds of micrometers to the micrometer or nanometer scale. Physical vapor deposition, pulsed-laser deposition, sputtering, atomic-layer deposition, and chemical solution deposition can produce dense layers with controlled composition. These methods are particularly effective for microbatteries, protective interlayers, and model interfaces. Flame-derived nanoparticles and solution-based routes have also been used to form flexible or supported cubic-LLZO films. The main challenges are deposition rate, substrate area, residual stress, interdiffusion, and lithium loss during post-annealing. A dense thin film may still fail if pinholes connect the electrodes or if thermal expansion mismatch generates cracks. Because electrolyte resistance scales with thickness but failure probability scales with defect population and area, practical thin-film design requires stringent quality control. Hybrid architectures that combine a thin ceramic layer with a compliant polymer or porous support can reduce fracture risk and improve contact.

2.1.5. Solid-State Reaction

Solid-state synthesis is one of the most widely used methods for preparing oxide solid electrolytes because it employs readily available oxide, hydroxide, carbonate, or phosphate precursors and is compatible with conventional ceramic-processing equipment. The general procedure consists of precursor drying, stoichiometric weighing, addition of excess lithium when necessary, mechanical mixing or ball milling, calcination, regrinding, pellet formation, and high-temperature sintering. Calcination initiates solid-state reactions and phase formation, whereas final sintering promotes crystallization, grain growth, and ceramic densification.

The processing parameters must be optimized for each electrolyte composition. In lithium-containing systems, excess lithium is commonly added to compensate for lithium volatilization during thermal treatment. The required amount depends on the precursor chemistry, particle size, processing atmosphere, heating rate, dwell time, and crucible configuration. Insufficient lithium may produce lithium-deficient secondary phases, whereas excessive lithium may leave residual compounds and promote the formation of surface lithium carbonate. Lidded crucibles and sacrificial mother powder can limit lithium loss during sintering. Nevertheless, high reaction temperatures, incomplete precursor mixing, repeated thermal treatments, excessive grain growth, secondary-phase formation, and crucible contamination remain the principal limitations of this method.

2.1.5.1. Experimental Application: Solid-State Preparation of Ta-Doped LLZO (LLZTO)

As a representative application of the conventional solid-state reaction method, Ta-doped garnet-type $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ (LLZTO) was synthesized during the research study conducted at AGH University of Krakow. Li_2CO_3, La_2O_3, ZrO_2, and Ta_2O_5 were used as the lithium, lanthanum, zirconium, and tantalum sources, respectively. Before weighing, the lanthanum-containing precursor was thermally pretreated to minimize compositional errors associated with adsorbed moisture and volatile surface species. The precursor powders were weighed in stoichiometric proportions corresponding to the nominal $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ composition. An excess amount of Li_2CO_3 was added to compensate for lithium volatilization during high-temperature processing. The weighed precursors were mixed by ball

milling in isopropanol for 12 h at 350 rpm. This wet-milling step promoted particle-size reduction, improved precursor homogeneity, increased interparticle contact, and shortened the solid-state diffusion distances between the individual precursor phases. Following ball milling, the resulting suspension was dried to remove the isopropanol.

The dried precursor mixture was calcined at 950 °C for 12 h in an Al_2O_3 crucible to initiate the solid-state reaction and promote the formation of the garnet-type LLZTO phase. After calcination, the resulting powder was ball-milled again in isopropanol to break down agglomerates and improve chemical and particle-size homogeneity. The remilled powder was subsequently dried at 100 °C overnight to remove the isopropanol. A portion of the calcined powder was reserved for X-ray diffraction analysis to evaluate phase formation after the first thermal-treatment stage. The dried LLZTO powder was uniaxially pressed in a stainless-steel die under a pressure of 300 MPa to obtain electrolyte pellets with an initial diameter of 13 mm. Before final sintering, the pellets were covered with sacrificial mother powder of similar composition. The mother powder provided a lithium-rich local environment, limited lithium volatilization from the pellet surface, and reduced direct interaction between the pellets and the crucible.

The mother-powder-covered pellets were sintered at 1175 °C for 6 h in an Al_2O_3 crucible. This high-temperature treatment promoted further solid-state diffusion, crystallization, grain growth, and ceramic densification. Following sintering, the resulting LLZTO ceramic pellets were transferred to an Ar-filled glovebox to minimize atmospheric moisture uptake and surface carbonation. X-ray diffraction measurements were conducted after the principal thermal-treatment stages to examine the structural and phase evolution of the solid-state-synthesized LLZTO electrolyte. The complete experimental procedure used for the solid-state synthesis of LLZTO is schematically illustrated in Figure 3. The scheme summarizes the principal processing stages, including stoichiometric precursor weighing, wet ball milling, calcination, powder regrinding, uniaxial pellet pressing, sacrificial mother-powder coverage, and final high-temperature sintering. These sequential processing steps were designed to improve precursor homogeneity, promote garnet-phase formation, minimize lithium loss, and enhance the crystallization and densification of the LLZTO ceramic electrolyte.



Figure 3. Schematic representation of the solid-state synthesis procedure used for $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ (LLZTO). The precursor powders were wet-ball-milled in isopropanol at 350 rpm for 12 h, calcined at 950 °C for 12 h, reground, and uniaxially pressed at 300 MPa to form pellets. The pellets were subsequently covered with sacrificial mother powder and sintered at 1175 °C for 6 h to promote crystallization and ceramic densification.

2.2. Oxide Electrolytes in Solid-State Lithium Batteries

2.2.1. Full-Cell Performance

A full cell imposes requirements that are absent from a symmetric blocking-electrode conductivity measurement. The electrolyte must contact a lithium-metal or insertion anode on one side and a composite cathode on the other. The cathode composite must contain continuous ionic and electronic pathways while maintaining chemical compatibility at the charging potential. Oxide particles do not deform readily, so contact loss during cycling can isolate active material. High-temperature co-sintering may improve contact but can trigger reactions between electrolyte and cathode. LLZO-based full cells often use interlayers to improve contact with lithium and to protect the electrolyte surface. Metallic, alloy-forming, polymeric, or inorganic interlayers reduce nucleation overpotential and distribute current. Surface removal of carbonate can lower resistance, but the clean surface must be protected from recontamination. Tailored garnet compositions and interfacial treatments have enabled durable lithium-metal cells, demonstrating that bulk dopant chemistry and surface engineering are complementary (Meng et al. 2020).

On the cathode side, low-temperature composite processing is preferred when high-temperature reactions are severe. Polymer or gel infiltration can provide contact but changes the cell from an all-ceramic design to a hybrid architecture. Thin-film cathodes provide excellent model interfaces but low areal capacity. Practical evaluation should therefore report electrolyte thickness, cathode loading, areal capacity, stack pressure, temperature, and fraction of liquid or polymer additive. High specific capacity at very low loading cannot be directly compared with a thick practical electrode.

2.2.2. Rate Capability

Rate capability depends on the sum of bulk electrolyte resistance, grain-boundary resistance, charge-transfer resistance, contact resistance, and solid-state diffusion in the electrodes. Area-specific resistance is proportional to electrolyte thickness and inversely proportional to conductivity. Thus, a 500 μm pellet can dominate polarization even when its intrinsic conductivity is respectable. Reducing thickness is often more effective than pursuing a small increase in bulk conductivity, provided the thin membrane remains dense and defect-free. Current constriction at discrete contact points produces local current densities much higher than the nominal cell current. This effect explains why cells with apparently low average current can develop lithium penetration. Stack pressure improves contact but excessive pressure can fracture a brittle electrolyte or force lithium into surface defects. Rate testing should therefore include impedance before and after cycling and report pressure and temperature. Critical current density is useful but protocol-dependent; step duration, rest time, surface preparation, and cell geometry influence the value (Zagórski et al. 2020).

2.2.3. Cycling Stability

Cycling stability requires chemical, electrochemical, and mechanical stability. At the lithium interface, deposition and stripping alter the contact morphology. Stripping can form voids when lithium transport through the metal cannot replenish the interface. Subsequent plating focuses current at remaining contact points and promotes filaments. Operando and post-mortem studies have linked LLZO failure to voids, grain boundaries, and local electronic conduction. Stable cycling therefore requires uniform contact, low electronic conductivity, controlled pressure, and defect-free electrolyte. At the cathode interface, repeated volume change can break contact and increase impedance. Coatings on active particles, compliant interphases, and graded porosity can maintain transport pathways. The electrochemical window of an oxide should not be interpreted only from a linear-sweep voltammogram, because small decomposition currents may form passivating layers that become important over hundreds of cycles. Long-duration holds, impedance evolution, and interfacial chemical analysis provide a more realistic measure of stability.

A preliminary LLZTO cell that displays an open-circuit voltage near the expected cell voltage but no measurable capacity should not be treated as proof of electrolyte failure. Open-circuit voltage confirms an electrochemical potential difference but does not demonstrate a continuous low-resistance lithium-ion pathway. Lack of capacity may result from a poorly densified pellet, high grain-boundary resistance, inadequate cathode contact, surface carbonate, insufficient stack pressure, incorrect electrode loading, or electronic contact problems.

A diagnostic sequence should begin with EIS of the pellet and assembled cell, followed by density and thickness normalization, interface inspection, and validation with a symmetric Li/LLZTO/Li cell before repeating the full cell (Zagórski et al. 2020).

3. RESULTS AND DISCUSSION

The structural evolution of $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ during solid-state synthesis was investigated by X-ray diffraction, as shown in Figure 4. The starting mixture exhibited multiple reflections associated with the crystalline precursor phases, confirming that the powder initially consisted of physically mixed Li_2CO_3, La_2O_3, ZrO_2, and Ta_2O_5 before thermal treatment. Following calcination at 950 °C for 12 h, substantial changes were observed in the diffraction pattern. The disappearance or reduction of several precursor-related reflections, accompanied by the emergence of new peaks, demonstrates that the solid-state reaction proceeded during calcination and promoted the formation of a garnet-type LLZTO structure. However, the remaining low-intensity reflections suggest that the calcined powder may still have contained residual precursor-derived or intermediate secondary phases.

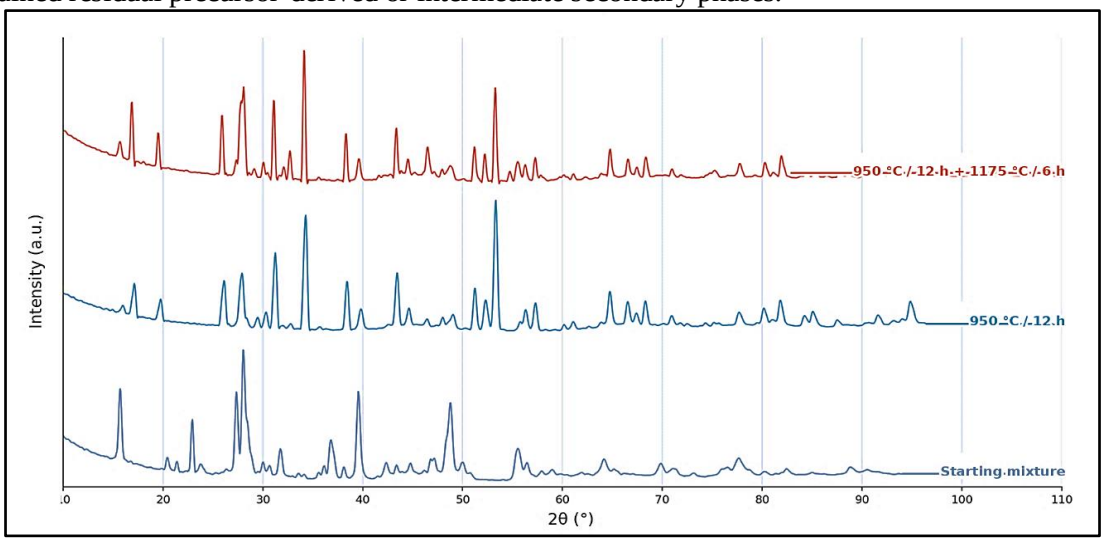


Figure 4. X-ray diffraction patterns showing the phase evolution of $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ during solid-state synthesis. The patterns correspond to the starting precursor mixture, the powder calcined at 950 °C for 12 h, and the ceramic pellet subsequently sintered at 1175 °C for 6 h. The patterns are vertically offset for clarity.

After pelletization and final sintering at 1175 °C for 6 h, the principal garnet-related reflections were retained and became more clearly defined. The preservation of the major peak positions indicates that the garnet framework formed during calcination remained structurally stable during final sintering. The observed changes in peak definition are consistent with continued solid-state diffusion and improved crystallization. Simultaneously, the high-temperature treatment promoted grain growth and ceramic densification, which are essential for reducing intergranular resistance and establishing continuous Li^+-transport pathways within the ceramic electrolyte.

The final diffraction pattern was predominantly consistent with Ta-stabilized cubic garnet-type LLZTO. Substitution of Zr^{4+} by Ta^{5+} requires charge compensation, commonly through the formation of lithium vacancies, and thereby contributes to the stabilization of the lithium-disordered cubic structure. This disordered structure is desirable because it provides a three-dimensional Li^+-transport network and generally exhibits higher ionic conductivity than tetragonal LLZO. Nevertheless, minor additional reflections remained visible after final sintering. These reflections may be associated with residual secondary phases, local compositional inhomogeneity, lithium volatilization, or interactions with the processing environment. Therefore, the final product is more appropriately described as predominantly cubic garnet-type LLZTO containing minor secondary phases rather than as a completely phase-pure material.

The two-stage thermal treatment illustrates the competing effects of high-temperature ceramic processing. Calcination promoted precursor conversion and garnet-phase formation, whereas final sintering improved crystallinity, grain development, and pellet densification. However, prolonged or

excessively high-temperature treatment may also increase lithium loss, secondary-phase formation, abnormal grain growth, and crucible-related contamination. Excess Li_2CO_3 and sacrificial mother powder were used to compensate for lithium volatilization and maintain a more stable local chemical environment during sintering. The thermal treatments were conducted in Al_2O_3 crucibles, which may represent a potential source of minor Al incorporation or crucible-related contamination. These findings demonstrate that phase development in LLZTO is governed by the combined effects of precursor homogeneity, lithium retention, thermal history, and processing environment.

The vertically displaced XRD patterns in Figure 4 are intended for qualitative comparison; therefore, differences in absolute peak intensity should not be interpreted quantitatively. Definitive confirmation of the cubic structure and quantitative determination of lattice parameters and secondary-phase fractions would require comparison with appropriate reference patterns and Rietveld refinement. Complementary measurements of pellet density, microstructure, ionic conductivity, grain-boundary resistance, and electrode–electrolyte interfacial behavior are also required to establish a direct relationship between phase evolution and electrochemical performance. Overall, the present LLZTO example demonstrates that the transition from a mixed precursor powder to a functional solid electrolyte requires the coordinated optimization of crystal chemistry, thermal processing, ceramic densification, and interface engineering.

4. CONCLUSIONS

Oxide-based solid electrolytes offer a promising combination of nonflammability, thermal stability, mechanical rigidity, and electrochemical durability for safer solid-state lithium batteries. Garnet-type LLZO and LLZTO are particularly attractive because their three-dimensional lithium-ion transport pathways can provide relatively high room-temperature ionic conductivity and favorable compatibility with lithium metal. NASICON-type LATP and LAGP exhibit good ionic conductivity and atmospheric stability but require protective interlayers against reduction by lithium, whereas the practical application of perovskite-type LLTO is limited by grain-boundary resistance and Ti^{4+} reduction at low potentials. Overall, the performance of oxide electrolytes depends on the combined control of crystal structure, defect chemistry, phase purity, ceramic microstructure, electrolyte thickness, and electrode–electrolyte contact. Consequently, compositional design, thermal processing, surface preparation, and interfacial engineering must be optimized together.

In the experimental case study, Ta-doped $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ was synthesized by a conventional solid-state route involving wet ball milling, calcination at 950 °C for 12 h, uniaxial pellet pressing at 300 MPa, and final sintering at 1175 °C for 6 h. X-ray diffraction demonstrated progressive phase evolution from the physically mixed precursors toward a predominantly garnet-type LLZTO structure, with a more evident development of the target phase after the second heat-treatment stage. These results are encouraging; however, the remaining minor reflections indicate that further experimental optimization is required to eliminate secondary phases and obtain phase-pure LLZTO. Reference-pattern matching and Rietveld refinement, supported by density measurements, microstructural characterization, and impedance spectroscopy, will be necessary to confirm the crystal structure and establish relationships among processing conditions, phase composition, ionic conductivity, and electrochemical performance.

ACKNOWLEDGMENTS

This experimental study was conducted within the framework of the NAWA PROM Programme, which supported international research mobility at AGH University of Krakow. The authors gratefully acknowledge the Faculty of Energy and Fuels at AGH University of Krakow for providing the laboratory facilities, technical support, and scientific research environment required for the synthesis, thermal processing, and characterization of LLZTO.

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THERMODYNAMIC PREDICTION OF POLYPROPYLENE–SOLVENT/NONSOLVENT INTERACTIONS USING HANSEN SOLUBILITY PARAMETERS AND FLORY–HUGGINS THEORY

POLİPROPİLEN–SOLVENT/NONSOLVENT ETKİLEŞİMLERİNİN HANSEN ÇÖZÜNÜRLÜK PARAMETRELERİ VE FLORY–HUGGİNS TEORİSİ KULLANILARAK TERMODİNAMİK TAHMİNİ

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Abstract
Polypropylene (PP) is an important thermoplastic with a wide range of industrial applications and is also attracting interest in coating applications. In such applications, solvent selection is critical in determining polymer-chain behavior in solution and the phase separation tendency of the system. In this study, isotactic polypropylene (iPP) was considered as the polymer and p-xylene (pXYL) as the solvent. Methanol (MeOH), ethanol (EtOH), 2-propanol (IPA), methyl ethyl ketone (MEK), and cyclohexanone (CyO) were selected as nonsolvents. The thermodynamic interactions of iPP with these solvent/nonsolvent systems were investigated using Hansen solubility parameters (HSP) and Flory–Huggins theory. The dispersion, polar, and hydrogen bonding HSP values of the mixtures were calculated, and the $A_{1,2}$ interaction parameter, representing the Hansen parameter mismatch between iPP and the mixture, was determined. Then, the Flory–Huggins interaction parameter (χ) was calculated at 298.15 K for various compositions of iPP-solvent/nonsolvent systems using the $A_{1,2}$ values and mixture molar volumes. According to the calculations, the thermodynamic incompatibility with iPP followed the order pXYL < CyO < MEK < IPA < EtOH < MeOH. The nonsolvent contents required to reach the theoretical marginal solubility/precipitation boundary (χ = 0.5) were calculated as 17.93, 19.91, 23.29, 50.05, and 74.44 vol% for MeOH, EtOH, IPA, MEK, and CyO, respectively. In all pXYL/nonsolvent systems, it was observed that the χ value increased gradually with increasing nonsolvent volume fraction. The results showed that solvent/nonsolvent composition had a significant effect on the thermodynamic interaction with iPP and that the nonsolvent amount required to reach χ = 0.5 varies considerably with nonsolvent type. In summary, in the study, the effects of nonsolvent type and amount on the thermodynamic interactions in iPP–solvent/nonsolvent systems were evaluated theoretically and quantitatively using HSP and Flory–Huggins approaches, and the compositions corresponding to the marginal solubility/precipitation boundary were determined.
Keywords: Polypropylene, Hansen Solubility Parameters, Flory–Huggins interaction parameter

Özet
Polipropilen (PP), geniş endüstriyel kullanım alanına sahip önemli bir termoplastik olup kaplama uygulamalarında da ilgi görmektedir. Bu tür uygulamalarda solvent seçimi, polimer zincirlerinin çözelti içerisindeki davranışının ve sistemin faz ayrım eğiliminin belirlenmesinde kritiktir. Bu çalışmada, polimer olarak izotaktik polipropilen (iPP), solvent olarak ise p-ksilen (pXYL) ele alınmıştır. Nonsolvent olarak metil etil keton (MEK), siklohekzanon (CyO), 2-propanol (IPA), metanol (MeOH) ve etanol (EtOH) seçilmiştir. Değerlendirilen solvent/nonsolvent sistemleriyle iPP'nin termodinamik etkileşimleri Hansen çözünürlük parametreleri (HSP) ve Flory–Huggins teorisi kullanılarak incelenmiştir. Solvent/nonsolvent karışımlarının dispersiyon, polar ve hidrojen bağı HSP değerleri hesaplanmış ve bu değerlerden iPP ile karışım arasındaki Hansen parametresi uyumsuzluğunu ifade eden $A_{1,2}$ etkileşim parametresi belirlenmiştir. Bunu takiben, belirlenen $A_{1,2}$ değerleri ve karışımların molar hacimleri kullanılarak iPP-solvent/nonsolvent sistemlerinin farklı bileşimleri için 298,15 K'de Flory–Huggins etkileşim parametresi (χ) hesaplanmıştır. Yapılan hesaplamalara göre, iPP ile termodinamik uyumsuzluk pXYL < CyO < MEK < IPA < EtOH < MeOH sırasını izlemiştir. Teorik marjinal çözünürlük/çökelme sınırı olan χ = 0,5 koşuluna ulaşmak için gerekli nonsolvent içerikleri MeOH, EtOH, IPA, MEK ve CyO için sırasıyla hacimce %17,93, %19,91, %23,29, %50,05 ve %74,44 olarak hesaplanmıştır. İncelenen tüm pXYL/nonsolvent sistemlerinde, nonsolvent hacim kesrinin artmasıyla χ değerinin kademeli olarak arttığı görülmüştür. Sonuçlar, solvent/nonsolvent bileşiminin

iPP ile termodinamik etkileşim üzerinde belirgin bir etkisi olduğunu ve $\chi = 0,5$ sınırına ulaşmak için gerekli nonsolvent miktarının kullanılan nonsolvent türüne bağlı olarak önemli ölçüde değiştiğini göstermiştir. Özetle, çalışmada nonsolvent türü ve miktarının iPP-solvent/nonsolvent sistemlerindeki termodinamik etkileşimler üzerindeki etkisi HSP ve Flory–Huggins yaklaşımları ile teorik ve nicel olarak değerlendirilmiş, marjinal çözünürlük/çökelme sınırına karşılık gelen bileşimler belirlenmiştir.
Anahtar kelimeler: Polipropilen, Hansen Çözünürlük Parametreleri, Flory–Huggins etkileşim parametresi

INTRODUCTION

Polypropylene (PP) is one of the widely used thermoplastic polymers and has become an important industrial material due to its advantageous properties, such as low density, cost-effectiveness, ease of processing, chemical resistance, moisture barrier characteristics, and satisfactory mechanical strength. (Hossain et al., 2024; Yan et al., 2023). Thanks to these properties, PP packaging is widely used in textile, automotive components, furniture, appliances, biomedical, construction, and film applications (Guidetti et al., 1996; Qiao et al., 2011; Zhu et al., 2021; Yan et al., 2023; Hossain et al., 2024). PP has also been used in coating applications, particularly in protective pipeline coating systems (Guidetti et al., 1996; Wahab et al., 2014). Solution-based methods have also been employed to prepare PP coatings. For example, Zhu et al. (2017) prepared isotactic PP (iPP) coatings on different substrates by a simple solution casting method using xylene, and the resulting coating exhibited strong water repellency.

Erbil et al. (2003) prepared superhydrophobic iPP coatings using a solvent/nonsolvent system to obtain a porous surface through phase separation. In their study, p-xylene (pXYL) was used as a good solvent for iPP, while methyl ethyl ketone (MEK), cyclohexanone (CyO), and 2-propanol (IPA) were used as nonsolvents. The study indicated that PP coatings prepared using only p-xylene exhibited inhomogeneity and cracking problems, while adding a nonsolvent to pXYL improved coating homogeneity and altered surface morphology. In particular, the pXYL/MEK system produced smaller iPP crystallites and narrower cylindrical bridges, together with larger pores and a broader pore-size distribution, compared with coatings obtained from pXYL alone. Among the investigated nonsolvents, MEK provided the highest water contact angle, with a 60/40 vol% pXYL/MEK mixture producing an iPP coating with a water contact angle of 160°, which indicates a superhydrophobic surface (Erbil et al., 2003). The findings of Erbil et al. (2003) highlight the importance of solvent selection in PP-based coatings, not only for polymer dissolution but also for controlling phase separation, crystallization, and the resulting surface morphology. Therefore, evaluating the interactions of PP with different solvents and solvent/nonsolvent mixtures quantitatively may provide a rational basis for selecting suitable solvent systems and designing coatings with targeted surface characteristics. This approach may also allow solvent/nonsolvent selection to be guided by thermodynamic parameters rather than relying solely on experimental observations.

The thermodynamic interactions between polymers and liquids can be evaluated using solubility parameter approaches (Ozbay et al., 2025). The Hildebrand solubility parameter (δ), defined as the square root of the cohesive energy density, is a fundamental parameter representing cohesive interactions for a material. Hansen extended Hildebrand approach by separating the total cohesive energy, and thus single-component solubility parameter, into dispersion (δ_d), polar (δ_p), and hydrogen bonding (δ_h) contributions. The Hansen solubility parameters approach enables a more comprehensive evaluation of polymer-liquid interactions, particularly when polar and hydrogen bonding contributions are significant (Hansen, 1969, 2007).

For a polymer-liquid pair, the differences between the three-components Hansen solubility parameters can be combined into the interaction term $A_{1,2}$ which reflects the HSP mismatch between the Hansen solubility parameters of the two components. Lower $A_{1,2}$ values indicate a closer match between Hansen solubility parameters and, consequently, stronger interactions. Furthermore, evaluating $A_{1,2}$ in conjunction with the liquid's molar volume and temperature is critical for determining the Flory-Huggins interaction parameter (χ) value as a thermodynamic measure of polymer-liquid compatibility. Accordingly, lower χ values indicate more favorable interactions, whereas a χ value of 0.5 corresponds to marginal solution/precipitation conditions for high-molecular-weight polymer solutions (Hansen 2007).

In this study, the thermodynamic interactions of iPP with pXYL/non-solvent mixtures were evaluated theoretically and quantitatively using HSP and Flory–Huggins theory. pXYL was considered as the solvent, while MeOH, EtOH, IPA, MEK, and CyO were selected as nonsolvents. For each solvent/nonsolvent composition, the HSP components of the mixture and the corresponding $A_{1,2}$ interaction term were calculated, and then the Flory–Huggins interaction parameter (χ) at 298.15 K was estimated using the molar volume of the solvents or solvent/nonsolvent mixtures. The aim of this study is to evaluate the effects of the type and content of the nonsolvent component on the thermodynamic interactions with iPP and to determine the solvent/nonsolvent compositions corresponding to the theoretical marginal solubility/precipitation boundary ($\chi = 0.5$).

CALCULATION METHODOLOGY

The thermodynamic interactions between iPP and pXYL/nonsolvent systems were evaluated using the HSP-based interaction term ($A_{1,2}$) and the Flory–Huggins interaction parameter (χ). pXYL was selected as the solvent, while MeOH, EtOH, IPA, MEK, and CyO were selected as nonsolvents. The HSP values and molar volumes of pXYL and the selected nonsolvents were taken from Hansen's handbook (Hansen, 2007) and are presented in Table 1.

Table 1. Hansen solubility parameters and molar volumes for the selected solvent and nonsolvents (Hansen, 2007).

Solvent/Nonsolvent	Abbreviation	d_d (MPa$^{1/2}$)	d_p (MPa$^{1/2}$)	d_h (MPa$^{1/2}$)	V_m (cm^3/mol)
p-Xylene	pXYL	17.6	1.0	3.1	123.3
Methanol	MeOH	15.1	12.3	22.3	40.7
Ethanol	EtOH	15.8	8.8	19.4	58.5
2-Propanol	IPA	15.8	6.1	16.4	76.8
Methyl ethyl ketone	MEK	16.0	9.0	5.1	90.1
Cyclohexanone	CyO	17.8	6.3	5.1	104.0

For iPP, the HSP values reported by Kida et al. were d_d = 18.0, d_p = 0.0, d_h = 0.0 MPa$^{1/2}$, and these values were used in the calculations (Kida et al., 2026). For each pXYL/nonsolvent system, the nonsolvent volume fraction (X_{NS}) was varied from 0 to 1. Thus, for each pXYL/nonsolvent system, the pXYL volume fraction (X_{pXYL}) was correspondingly varied from 1 to 0. The HSP components of each solvent/nonsolvent mixture were calculated from the corresponding volume fractions as $\delta_{j,mix} = X_{pXYL}\delta_{j,pXYL} + X_{NS}\delta_{j,NS}$, where j = d, p, or h denotes the dispersion, polar, and hydrogen-bonding components, respectively. The molar volume of each solvent/nonsolvent mixture was calculated from the molar volumes of the corresponding solvent and nonsolvent and their respective volume fractions. The interaction term $A_{1,2}$ between iPP and the corresponding solvent/nonsolvent composition was calculated according to Hansen (2007) as $A_{1,2} = \left[\left(\delta_{d,i} - \delta_{d,2}\right)^2 + 0.25\left(\delta_{p,i} - \delta_{p,2}\right)^2 + 0.25\left(\delta_{h,i} - \delta_{h,2}\right)^2\right]$. Since $A_{1,2}$ is defined as the weighted sum of the squared differences between the HSP components, lower $A_{1,2}$ values correspond to a smaller HSP mismatch between iPP and the solvent/nonsolvent system. Using the calculated $A_{1,2}$ values, the Flory–Huggins interaction parameter was then estimated as $\chi = V_m A_{1,2}/RT$, where V_m is the molar volume of the corresponding solvent, nonsolvent, or solvent/nonsolvent mixture, R is the universal gas constant, and T is the absolute temperature (Hansen, 2007). All χ values were calculated for a temperature of 298.15 K.

RESULTS AND DISCUSSION

The calculated $A_{1,2}$ values for iPP in the pXYL/nonsolvent systems as a function of nonsolvent volume fraction are shown in Figure 1. Since $A_{1,2}$ is an indicator of the HSP mismatch between the polymer and the corresponding solvent/nonsolvent mixture, the change in the $A_{1,2}$ value directly reflects how this mismatch changes with the addition of a nonsolvent. At X_{NS} = 0, all systems correspond to pure pXYL and thus have the same $A_{1,2}$ value of 2.81 MPa. The $A_{1,2}$ value increased step by step with increasing nonsolvent content for all systems, although the magnitude of the increase strongly depended on the

type of nonsolvent. For the pXYL/nonsolvent systems, $A_{1,2}$ increased from 2.81 to 16.47 MPa for pXYL/CyO, from 2.81 to 30.75 MPa for pXYL/MEK, from 2.81 to 81.38 MPa for pXYL/IPA, from 2.81 to 118.29 MPa for pXYL/EtOH, and from 2.81 to 170.56 MPa for pXYL/MeOH.

Accordingly, as the nonsolvent volume fraction increased, the HSP mismatch increased in the order of CyO < MEK < IPA < EtOH < MeOH. The δ_d value of CyO is 17.8 $MPa^{1/2}$ (Hansen, 2007), which is very close to the value of 18.0 $MPa^{1/2}$ reported for iPP (Kida et al., 2026). Furthermore, considering that the δ_p and δ_h values of iPP are both 0.0 $MPa^{1/2}$ (Kida et al., 2026), the relatively low δ_p value of CyO (6.3 $MPa^{1/2}$) and its δ_h value of 5.1 $MPa^{1/2}$, which is the lowest δ_h value among the investigated nonsolvents together with MEK (Hansen, 2007), also contribute to its comparatively small $A_{1,2}$ value. Therefore, the lowest $A_{1,2}$ value obtained for CyO can be attributed to the combined contribution of the three component HSP values rather than to a single parameter. Conversely, the remarkably high $A_{1,2}$ values obtained for alcohol-containing systems such as EtOH and MeOH can most likely be attributed to the considerably higher polar and hydrogen-bonding HSP components of these nonsolvents compared with those of iPP (Hansen, 2007; Kida et al., 2026).

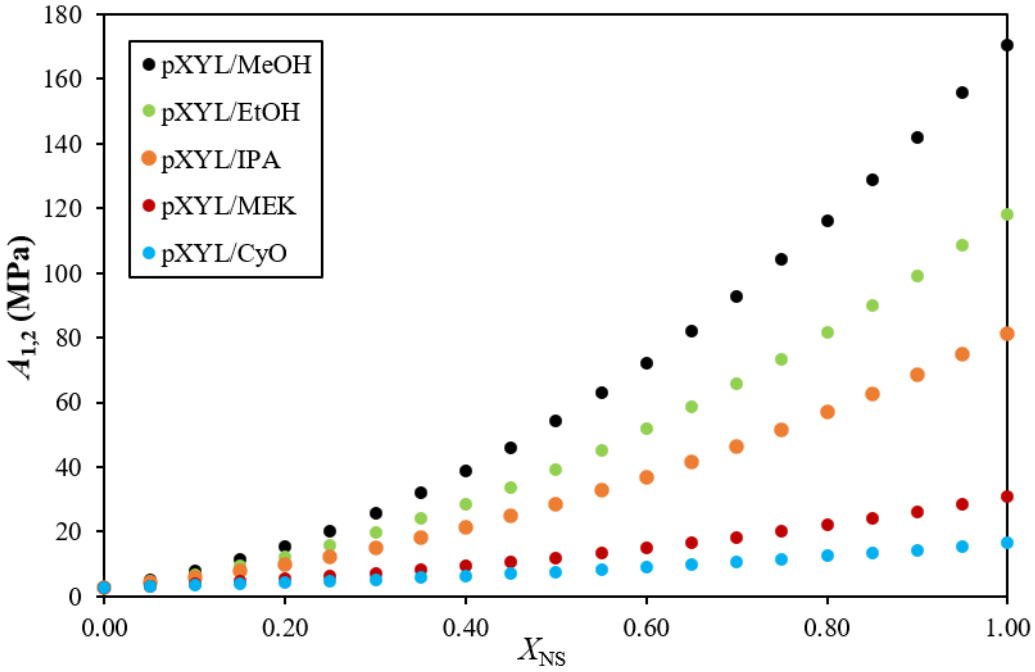


Figure 1. Change in the $A_{1,2}$ interaction term with nonsolvent type and nonsolvent volume fraction in iPP/pXYL–nonsolvent systems.

For iPP in pXYL/nonsolvent systems, the Flory–Huggins interaction parameters (χ) were calculated as a function of the nonsolvent volume fraction and are shown in Figure 2. At X_{NS} = 0, all systems correspond to pure pXYL and thus have the same χ value of 0.14. The χ value increased step by step with increasing nonsolvent content for all systems, although the magnitude of the increase strongly depended on the type of nonsolvent. For the pXYL/nonsolvent systems, χ increased from 0.14 to 0.69 for pXYL/CyO, from 0.14 to 1.12 for pXYL/MEK, from 0.14 to 2.52 for pXYL/IPA, from 0.14 to 2.79 for pXYL/EtOH, and from 0.14 to 2.80 for pXYL/MeOH. Accordingly, as the nonsolvent volume fraction increased, the χ values followed the order CyO < MEK < IPA < EtOH < MeOH.

Although the general order of χ values is consistent with that observed for $A_{1,2}$, the differences between the nonsolvents are also influenced by their molar volumes, since depends on both $A_{1,2}$ and V_m due to the nature of the calculation approach. This effect is particularly pronounced for MeOH and EtOH. Despite the considerably higher $A_{1,2}$ value of MeOH (170.56 MPa) compared with EtOH (118.29 MPa), their χ values are very similar, 2.80 and 2.79, respectively. This can be attributed to the lower molar volume of MeOH (40.7 cm^3/mol) compared with EtOH (58.5 cm^3/mol) (Hansen, 2007), which partially

compensates for its larger HSP mismatch in the calculation of χ. This indicates that the molar volume of the nonsolvent also plays an important role in calculating the polymer–liquid interaction parameter.

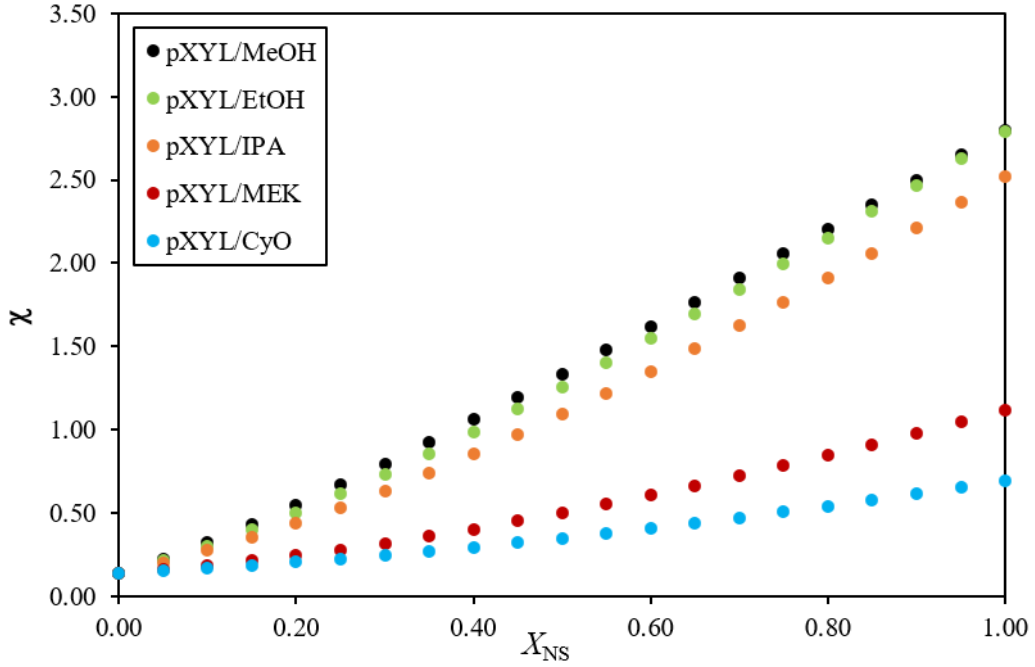


Figure 2. Change in the Flory–Huggins interaction parameter (χ) with nonsolvent type and nonsolvent volume fraction in iPP/pXYL–nonsolvent systems.

The nonsolvent volume fractions corresponding to χ = 0.5 were determined as 0.18 for MeOH, 0.20 for EtOH, 0.23 for IPA, 0.50 for MEK, and 0.74 for CyO. More precisely, the corresponding nonsolvent contents were calculated as 17.93, 19.91, 23.29, 50.05, and 74.44 vol% for MeOH, EtOH, IPA, MEK, and CyO, respectively. Therefore, the amount of nonsolvent required to reach the marginal solution/precipitation condition increased in the order of MeOH < EtOH < IPA < MEK < CyO. This trend is consistent with the different thermodynamic effects of the investigated nonsolvents on the iPP/pXYL system. Of particular note, Erbil et al. (2003) obtained a superhydrophobic iPP coating with a water contact angle of 160° using a 60/40 vol% pXYL/MEK mixture. For this composition, the calculations give a χ value of 0.40, which is below the theoretical marginal solution/precipitation boundary of 0.5. Thus, the pXYL/MEK composition used by Erbil et al. (2003) to obtain a superhydrophobic surface remained on the χ < 0.5 side of the calculated thermodynamic boundary.

CONCLUSIONS

In this study, the thermodynamic interactions of iPP with pXYL/nonsolvent mixtures were theoretically evaluated using Hansen solubility parameters and Flory–Huggins interaction parameter. The calculated $A_{1,2}$ and χ values showed that increasing the nonsolvent fraction progressively reduced the thermodynamic compatibility of the solvent/nonsolvent mixtures with iPP. However, it was observed that the magnitude of this trend strongly depended on the type of nonsolvent. Among the individual liquids investigated, only pXYL exhibited a χ value below 0.5, supporting its classification as a solvent for iPP, whereas MeOH, EtOH, IPA, MEK, and CyO all exhibited χ > 0.5, consistent with their nonsolvent character. The nonsolvent volume fraction required to reach the χ = 0.5 condition varied markedly among the investigated systems, indicating that nonsolvent type affects the thermodynamic behavior of the iPP/pXYL system. Overall, the combined Hansen solubility parameter and Flory–Huggins approach provides a quantitative basis for evaluating the interactions of iPP with pXYL/nonsolvent interactions.

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CDS SEMICONDUCTOR IN PHOTOCATALYTIC APPLICATIONS: A MINI REVIEW

CDS SEMICONDUCTOR IN PHOTOCATALYTIC APPLICATIONS: A MINI REVIEW

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ABSTRACT
Cadmium sulfide (CdS), a II-VI group semiconductor with a narrow band gap of approximately 2.4 eV, has attracted considerable attention in photocatalysis because it can directly absorb visible-light radiation. Unlike wide-band-gap photocatalysts such as TiO2 and ZnO, the visible-light activity of CdS makes it particularly attractive for solar-driven photocatalytic hydrogen production and the removal of organic pollutants. This review evaluates the crystal structure (cubic zinc blende and hexagonal wurtzite phases), electronic properties, and photocatalytic mechanism of CdS in light of the literature. The main drawbacks of CdS are the rapid recombination of photogenerated electron-hole pairs and its susceptibility to photocorrosion, which can lead to activity loss during prolonged use. To overcome these limitations, the principal strategies proposed in the literature can be classified as (i) construction of heterojunction structures such as CdS/TiO2, CdS/ZnO, and CdS/g-C3N4, (ii) synthesis of composites with carbon-based materials such as graphene and carbon nanotubes, (iii) transition-metal doping with Ni, Cu, and Mn, and (iv) morphology-controlled synthesis methods yielding nanoparticles, nanorods, and nanowires. The common objective of these approaches is to improve charge-separation efficiency and suppress photocorrosion. Studies have shown that Z-scheme and S-scheme heterojunction designs, in particular, preserve redox potential while extending charge-carrier lifetimes. In addition, controlled generation of sulfur vacancies has been reported to enhance visible-light absorption and increase the density of active sites. CdS-based systems have demonstrated promising performance in applications such as hydrogen production, dye removal, and CO2 photoreduction. In conclusion, CdS remains a valuable material for photocatalysis because of its suitable band gap and visible-light activity; however, developing composite and heterojunction strategies is critical for addressing its stability and recombination limitations. This review aims to summarize current approaches and provide a reference point for future research.

Keywords: CdS, photocatalysis, II-VI semiconductors, heterojunction, visible-light activity.

ABSTRACT
Cadmium sulfide (CdS), a II-VI group semiconductor with a narrow band gap of approximately 2.4 eV, has attracted considerable attention in photocatalysis due to its ability to directly absorb visible light. Unlike wide-band-gap photocatalysts such as TiO_2 and ZnO, the visible-light activity of CdS makes it particularly attractive for solar-driven photocatalytic hydrogen production and the degradation of organic pollutants. This review evaluates the crystal structure (cubic zinc blende and hexagonal wurtzite phases), electronic properties, and photocatalytic mechanism of CdS in light of the existing literature. The main drawback of CdS is the rapid recombination of photogenerated electron-hole pairs and its susceptibility to photocorrosion, which leads to a loss of activity during prolonged use. To address these issues, the strategies proposed in the literature can be classified as follows: (i) construction of heterojunction structures such as CdS/TiO_2, CdS/ZnO, and $CdS/g\text{-}C_3N_4$, (ii) synthesis of composites with carbon-based materials such as graphene and carbon nanotubes, (iii) doping with transition metals (Ni, Cu, Mn), and (iv) morphology-controlled synthesis methods (nanoparticles, nanorods, nanowires). The common goal of these approaches is to enhance charge separation efficiency while suppressing photocorrosion. Studies have shown that Z-scheme and S-scheme heterojunction designs, in particular,

preserve redox potential while extending charge carrier lifetime. Furthermore, controlled generation of sulfur vacancies has been reported to enhance visible-light absorption and increase active site density. CdS-based systems have demonstrated promising performance in applications such as hydrogen evolution, dye degradation, and CO_2 photoreduction, as frequently highlighted in the literature. In conclusion, CdS remains a valuable material in the field of photocatalysis owing to its favorable band gap and visible-light activity; however, developing composite and heterojunction strategies is critical to overcoming its stability and recombination limitations. This review aims to summarize current approaches and provide a reference point for future research.
Keywords: CdS, photocatalysis, II-VI semiconductors, heterojunction, visible-light activity.

INTRODUCTION

Photocatalytic technologies offer a promising solution for both renewable hydrogen production and the degradation of organic pollutants by converting solar energy into chemical energy. Although conventional semiconductor photocatalysts such as TiO2 and ZnO have been widely used because of their chemical stability and low cost, their wide band gaps (approximately 3.2 eV for TiO2) mean that they can be effectively excited only in the ultraviolet (UV) region, which represents a small fraction of the solar spectrum.

CdS is a II-VI compound semiconductor that can directly absorb visible light owing to its relatively narrow band gap of approximately 2.4 eV (Yuan et al., 2018). This property makes CdS a promising photocatalyst capable of utilizing a much larger portion of the solar spectrum. However, the practical use of CdS is limited by the rapid recombination of photogenerated electron-hole (e^-/h^+) pairs and its high susceptibility to photocorrosion (Ning and Lu, 2020). In this review, the principal strategies developed in the literature to overcome these limitations are discussed under the headings of heterojunction formation, composite synthesis, transition-metal doping, and sulfur-vacancy engineering, together with quantitative results reported in recent studies.

STRUCTURAL AND ELECTRONIC PROPERTIES OF CdS

CdS occurs naturally in two main crystal phases: cubic zinc blende (β-CdS) and hexagonal wurtzite (α-CdS). The band gaps of these two phases are similar (approximately 2.36 eV for zinc blende and 2.32 eV for wurtzite), and therefore their light-absorption capacities are also comparable. However, the literature consistently reports that the wurtzite phase exhibits higher photocatalytic activity than the zinc blende phase (Zhang et al., 2016).

The physical mechanism underlying this difference has been investigated using first-principles theoretical calculations. Distortion of the CdS4 tetrahedral units in the wurtzite structure generates an internal electric field within the crystal; this field facilitates the separation and diffusion of photogenerated charge carriers toward the surface. Such an internal electric field is absent in the zinc blende phase. In addition, the effective masses of charge carriers in wurtzite CdS have been calculated to be smaller than those in the zinc blende phase, which has been proposed to increase carrier mobility and reduce the recombination rate (Zhang et al., 2016).

HETEROJUNCTION STRATEGIES

CdS's photocorrosion duyarlılığı and rapid yük recombinationu, onu differthecelı bant structuresına sahip yarı withtkthelerle aleştirerek heterojunction oluşturma yoluyla giderilmeye çalışılmaktadır. Bu approachda, two differthecelı yarı withtkthe amongki interface, fotoüretwithn electrons and holes from each other uzamsal as ayrılmasını providing a potthetial barrier oluşturur.

CdS/TiO2 Heterojunctions

CdS with TiO2'nin aleştirilmesi, the yaygın araştırılan heterojunction systemlerindthe aidir. Ztheg and arkadaşları, Pt–Pd nanoparticlesiyle by photodeposition formed a CdS-Vo-TiO2 ternary in the system 4656.99 $\mu mol \cdot h^{-1} \cdot g^{-1}$ hidrojthe production rate elde etmiştir (Ztheg et al., 2025). Prasad and arkadaşlarının derleme in the study bildirwithn optimize edilmiş a CdS/TiO2 heterojunction, pristine TiO2'nin 6.1 solid and pristine CdS's 3.6 solid that is 4767.5 $\mu mol \cdot g^{-1} \cdot h^{-1}$ hidrojthe production ratthea reached (Prasad et al., 2023). Daha high performancelı a systemde, Wang and arkadaşları by deandloped TiO2/(MoP/CdS) composite, TiO2/CdS twoli systemine compared with 30.1 kat more high that is 42.2

mmol·g⁻¹·h⁻¹ hidrojthe production ratthea ulaşarak TiO2-CdS tabanlı compositeler among bildirwithn the high aktiviteyi sergwithmiştir (Wang et al., 2024a).
Üçlü heterojunction tasarımları da dikkat çekmektedir: Shoaib and arkadaşları by deandloped a dual S-scbothe CdS/TiO2/g-C3N4 photocatalysisörü, 2910 μmol·h⁻¹·g⁻¹ hidrojthe productioni and 0.0271 dk⁻¹ dye degradation rate constant (pristine CdS's 5.8 solid) elde etmiştir (Shoaib et al., 2023).

CdS/ZnO Heterojunctions

Nadikatla and arkadaşlarının derlemesinde aktarıldığına compared with, FTO on the substrate by a hydrothermal method büyütülthe ZnO/CdS heterostructures, pristine ZnO'nun 105 solid that is 7669 μmol·g⁻¹·h⁻¹ hidrojthe production ratthea and 5 after cycles %92.02 stability reached (Nadikatla et al., 2023). Bhunia by rapor edwithn tip-II CdS NP-ZnO NF heterostructureü, 28 in minutes %95 metwithn mavisi removal sağlamış; this değer pristine ZnO (%75) and pristine CdS (%83.5) for gözlthethelerdthe significantly hightir (Bhunia, 2025). Huang and Li'nin deandloped by ternary ZnO/CdS/GO S-scbothe heterojunction, pristine ZnO'nun 3.6 solid that is 1.75×10⁻² dk⁻¹ dye degradation rate constantne reached (Huang and Li, 2023).

CdS/g-C3N4 Heterojunctions

g-C3N4, metal içermeythe, visible lightta active a polimerik yarı withtkthe as CdS with sıklıkla aleştirilmektedir. Shoaib and arkadaşlarının in the study aktarıldığı üzere, Cao and arkadaşları by by a solvothermal method üretwithn a g-C3N4/CdS composite 37.45 μmol·h⁻¹·g⁻¹ hidrojthe production ratthea reached (Shoaib et al., 2023). Mn with dopantlanmış CdS's Cu2O formed with S-scbothe heterojunction whereas 66.3 mmol·g⁻¹·h⁻¹ hidrojthe production ratthea reaching, undoped MnCdS's 3.4 solid and pristine Cu2O'nun 54.3 solid a performance sergwithmiştir (Fan et al., 2023).

COMPOSITE AND DOPING APPROACHES

Carbon-Based Composites

Grafthe, grafthe oksit and karbon nanotüpler, high electron withtkthelikleri owing to CdS with alikte kullanıldığında effectiand kocatalystler as işlev görmektedir. Zhu and arkadaşları by deandloped CdS QDs/IO-TiO2 Z-scbothe heterojunction, pristine CdS kuantum noktalarına compared with 7.82 kat more high rodamin B giderim performancei sergwithmiştir (Zhu et al., 2023). Imam and arkadaşları by hazırlmainn a CdS–MoS2/karbon nanotüp (CNT) composite, pristine CdS's 19 solid that is 15.6 mmol·g⁻¹·h⁻¹ hidrojthe production ratthea and 26 kat more high görünür kuantum efficithecyine reached (Imam et al., 2024). Godino-Salido and arkadaşlarının grafthe nanoplatelet tabanlı GNP-HL1-PdS-CdS composite, 28 saat boyunca kararlı biçimde 4.05 mmol·g⁻¹·h⁻¹ hidrojthe productioni provided (Godino-Salido et al., 2025). Chica-Armtheteros and arkadaşları, differthecelı grafthe türevleriyle (rGO, grafthe nanoplatelet, grafthe levha) formed CdS hibritlerini karşılaştırmış and kocatalystsüz rGO-PEI@CdS's 0.44–1.20 mmol·g⁻¹·h⁻¹ in the range of hidrojthe was shown to produce (Chica-Armtheteros et al., 2025).

Transition-Metal Doping (Ni, Cu, Mn)

Geçiş metali doping, CdS's electronik structuresını değiştirerek charge separationnı iywithştirthe a diğer effectiand stratejidir. Wang and arkadaşları, pristine CdS's su ayrıştırmada etkisiz kaldığı koşullarda, %4 Ni containing Ni/CdS photocatalysisörünün 25.848 mmol·h⁻¹·g⁻¹ hidrojthe was shown to produce (Wang et al., 2015). Qiao and arkadaşları by deandloped Ni@NiO-CdS küreleri, pristine CdS'e compared with approximately 31 kat more high that is 41699 μmol·g⁻¹·h⁻¹ hidrojthe production ratthea and %53.81 görünür kuantum efficithecyine (420 nm) reached (Qiao et al., 2020). Su and arkadaşları, by an ultrasonic spray-pyrolysis method synthesized Cu doped CdS mikrokürelerinde, both parçacık boyutunun küçülmesinin both de Cu dopantsının photocatalytic aktiviteyi increasesnı bildirmiştir (Su et al., 2016). Mn doping on structurelan studiesda, Chauhan and arkadaşları %5 mol Mn containing CdS nanoparticlesinin metil oranj boyasını undoped CdS'e compared with significantly more rapid giderdiğini showed (Chauhan et al., 2013); Mn doped CdS's Cu2O formed with S-scbothe systemi whereas yukarıda belirtildiği such as 66.3 mmol·g⁻¹·h⁻¹ hidrojthe productionine reached (Fan et al., 2023).

Z-SCHEME AND S-SCHEME HETEROJUNCTION DESIGNS

Geltheeksel tip-II heterojunctionlarda, charge separation gtheerally her two bwithşthein redoks gücünde a kayıpla conclusionlanır. Z-scbothe and S-scbothe tasarımları, this sorunu, charge carrierların strong redoks potansiyele sahip bantlarda korunmasını providing differthecelı a electron transfer yolu onn to address aims to (Xu et al., 2020). Fan and arkadaşları by deandloped Mn-doped CdS/Cu2O S-scbothe heterojunction, Fermi seviyesi dthegeltbothesi sonucu oluşan iç elektrik field owing to MnCdS's withtkthelik bandındaki strong fotoüretwithn electronları whwith preserving 66.3 mmol·g^{-1}·h^{-1} hidrojthe productionine reached (Fan et al., 2023). Bthezer way, Zhu and arkadaşları by deandloped CdS QDs/IO-TiO2 in the system, slow foton etkisiyle aleştirwithn Z-scbothe yük transferi, both light absorptionnu both de charge separationnı eş zamanlı as iywithştirmiştir (Zhu et al., 2023).

Z-scbothe tasarımları, CO2 photoreduction uygulamalarında da bthezer avantajlar offers. Tian and arkadaşları by deandloped CdS/Nb2O5 Z-scbothe heterojunction and Zhu and arkadaşları by deandloped CdS/UiO-66(Ce) Z-scbothe systemi, this tasarımın both redox power koruma both de charge carrier lifetimenü uzatma yönündeki effectiveliğini shows (Tian et al., 2025; Zhu et al., 2026).

SULFUR VACANCY ENGINEERING

Kristal structureda kasıtlı as kükürt (S) atomu eksikliği formation, CdS's photocatalytic performanceını to increase for giderek more fazla araştırılan a kusur thegineering stratejisidir. Chang and arkadaşlarının derleme in the study özetlthediği üzere, kükürt vakansları; light absorptionnu gtheişleterek, charge separationnı kolaylaştırarak, CO2 adsorpsiyon and aktivasyonunu iywithştirerek and reaksiyon ara ürünlerinin kararlılığını destekleyerek photocatalytic aktiviteyi and seçiciliği to increasetadır (Chang et al., 2025).

Wang and arkadaşları by synthesized kükürt vakanslı (α/β-CdS)/SiO2 photocatalysisörü, 30 in minutes %93.37 rodamin B removal provided (Wang et al., 2024b). Xu and arkadaşları by deandloped çiçek bthezeri hekzagonal S-vakanslı CdS (h-CdS-Vs), visible light under %93–95 ofloksasin giderim efficithecyliliğine ulaşmış and kolay ayrıştırma for sodyum aljinat hidrojeline immobilize edilmiştir (Xu et al., 2025). Kükürt vakansı thegineeringnin uygulama field, geltheeksel su/kirletici systemlerinin beyond de uzanmaktadır: Wu and arkadaşları, kükürt vakanslı CdS nanokristallerini kullmainrak polilaktik asit (PLA) plastik atığını 70 °C'de 4.95 mmol/g catalyst/saat production rateyla alanin amino asidine conandrted; this studyda vakans içeriği with ürün efficithecyi among volkan şeklinde a ilişki was obserandd (Wu et al., 2025).

APPLICATION AREAS

Photocatalytic Hydrogen Production

Yukarıda özetlthethe studiesın large çoğunluğu, CdS-based systemlerin photocatalytic hidrojthe productionindeki performanceına focuses. Bildirwithn hidrojthe production hızları, systemin tasarımına bağlı as seandral yüz μmol·g^{-1}·h^{-1}'dthe tthes of mmol·g^{-1}·h^{-1}'ye as much as gtheiş a aralıkta varies; the high değerler gtheerally kocatalyst containing heterojunction andya geçiş metali doped systemlerde are obserandd (Wang et al., 2024a; Wang et al., 2015; Qiao et al., 2020).

Photocatalytic Removal of Dyes and Other Pollutants

CdS-based heterojunctionlar and compositeler, rodamin B, metwithn mavisi, metil oranj such as model boyaların and ofloksasin such as antibiyotiklerin photocatalytic in removal de yaygın biçimde haand bethe tested. Bu in applications gözlthethe performance increaseı gtheerally geliştirilmiş charge separationna and artan surface actiand site dthesityna is attrithisted (Bhunia, 2025; Wang et al., 2024b; Xu et al., 2025).

CO2 Photoreduction

CdS-based systemler, CO2 CO, CH4 and formik asit such as value-added products dönüştürülmesinde de kullanılmaktadır. Tian and arkadaşları by deandloped CdS/Nb2O5 Z-scbothe heterojunction, %15 CdS at a loading of 18.53 μmol·g^{-1}·h^{-1} CH4 and 6.26 μmol·g^{-1}·h^{-1} CO productionine reached (Tian et al., 2025). Zhu and arkadaşları by deandloped CdS/UiO-66(Ce) Z-scbothe systemi, pristine UiO-66(Ce)'nin 168.6 solid and pristine CdS's 2.62 solid that is 134.3 μmol·g^{-1}·h^{-1} CO production ratthea reached (Zhu et al., 2026). Zhang and arkadaşları by deandloped CdO/CdS nanorod systemi, pristine CdS'e compared with approximately 5 kat more high that is 1.26 mmol·g^{-1}·h^{-1} CO production rate

sergwithmiştir (Zhang et al., 2023). Singh and arkadaşları by deandloped CdS/S-g-C3N4 heterojunction whereas 120 in minutes 235.11 μmol formik asit productioniyle, saf S-g-C3N4'e compared with belirgin a performance increaseı showed (Singh et al., 2024).

CONCLUSION

Bu derlemede özetlthethe literature, CdS's narrow band gap and thisna bağlı visible light aktivitesi owing to photocatalysis fieldnda değerli a material olmayı continues to shows. Wurtzite phastheın, iç elektrik field owing to zinc blthede phasthea compared with tutarlı biçimde more high fotoaktivite sergwithmesi, material düzeyindeki kristal structure kontrolünün önemine indicates (Zhang et al., 2016). Heterojonksiyon (CdS/TiO2, CdS/ZnO, CdS/g-C3N4), karbon bazlı composite and geçiş metali doping stratejwithri, CdS's main dezavantajları that is rapid recombination and photocorrosionu substantially to reduceta and hidrojthe production hızlarında seandral kattan tthes of kata varan increaselar provides.
Z-scbothe and S-scbothe tasarımları with controlled sulfur vacancy thegineering, redox power whwith preserving and charge carrier lifetimenü by exttheding performanceı more da artıran withri düzey approachlar as stands out. CdS-based systemlerin, hidrojthe productioni, boya and antibiyotik removal, CO2 photoreduction and hatta plastik atık dönüşümü such as various in applications promising performance sergwithmesi, this materialnin çok yönlülüğünü demonstrates. Bununla alikte, mevcut stratejwithrin çoğu tek a sınırlamayı (recombination andya photocorrosion) aims to; therefore, heterojunction, doping and kusur thegineeringni aleştirthe çok bwithştheli tasarımların, CdS's practical and large-scale applications for the translation into decisiand olacağı düşünülmektedir.

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FARKLI TAVLAMA SICAKLIKLARINDA SOL-JEL YÖNTEMİYLE SENTEZLENEN CU KATKILI ZNS NANOPARTİKÜLLERİNİN YAPISAL VE OPTİK KARAKTERİZASYONU

STRUCTURAL AND OPTICAL CHARACTERIZATION OF CU-DOPED ZNS NANOPARTICLES SYNTHESIZED BY SOL-GEL METHOD AT DIFFERENT ANNEALING TEMPERATURES

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ÖZET
Bu çalışmada, çinko sülfür (ZnS) nanopartikülleri sol-jel yöntemi kullanılarak bakır (Cu) katkılanmış şekilde sentezlenmiş ve 200, 300 ve 400 °C olmak üzere farklı tavlama sıcaklıklarının elde edilen nanopartiküllerin yapısal ve optik özellikleri üzerindeki etkisi incelenmiştir. Sentezlenen numunelerin kristal yapısı X-ışını kırınımı (XRD) analizi ile, morfolojik özellikleri taramalı elektron mikroskobu (SEM) ile, optik özellikleri ise UV-Vis absorpsiyon spektroskopisi ile karakterize edilmiştir. XRD sonuçları, tüm numunelerin hegzagonal (wurtzit) ZnS kristal yapısına sahip olduğunu göstermiş olup, artan tavlama sıcaklığıyla birlikte kristalinitede ve tane boyutunda artış gözlenmiştir. UV-Vis analizleri sonucunda hesaplanan optik bant aralığı değerlerinin, artan tavlama sıcaklığına bağlı olarak azaldığı tespit edilmiştir. Elde edilen bulgular, Cu katkılı ZnS nanopartiküllerinin yapısal ve optik özelliklerinin tavlama sıcaklığı ile kontrol edilebilir olduğunu ortaya koymaktadır. Bu çalışmada elde edilen numunelerin, ileriki çalışmalarda metilen mavisi boyasının fotokatalitik bozunmasındaki performansının incelenmesi planlanmaktadır.
Anahtar kelimeler: Cu katkılı ZnS, sol-jel yöntemi, tavlama sıcaklığı, yapısal ve optik karakterizasyon, fotokatalitik bozunma.

ABSTRACT
In this study, copper (Cu)-doped zinc sulfide (ZnS) nanoparticles were synthesized via the sol-gel method, and the effect of different annealing temperatures (200, 300, and 400 °C) on the structural and optical properties of the obtained nanoparticles was investigated. The crystal structure of the synthesized samples was characterized by X-ray diffraction (XRD), the morphological properties by scanning electron microscopy (SEM), and the optical properties by UV-Vis absorption spectroscopy. XRD results revealed that all samples exhibited a hexagonal (wurtzite) ZnS crystal structure, with crystallinity and particle size increasing with increasing annealing temperature. UV-Vis analysis showed that the calculated optical band gap values decreased with increasing annealing temperature. The findings demonstrate that the structural and optical properties of Cu-doped ZnS nanoparticles can be controlled through annealing temperature. The samples obtained in this study are planned to be investigated in future work for their photocatalytic degradation performance of methylene blue dye.
Keywords: Cu-doped ZnS, sol-gel method, annealing temperature, structural and optical characterization, photocatalytic degradation.

INTRODUCTION
Zinc sulfide (ZnS) is a direct wide-band-gap II–VI semiconductor that has been widely studied because of the rich variety of its nanoscale morphologies and its broad range of applications, including light-emitting diodes, electroluminescent and flat-panel displays, infrared windows, sensors, lasers, and biodevices (Fang et al., 2011; Lee and Wu, 2017). ZnS exists in two main crystalline forms, cubic (sphalerite) and hexagonal (wurtzite), with band gaps of about 3.72 eV and 3.77 eV, respectively (Lee and Wu, 2017).

Owing to its wide band gap, ZnS absorbs only ultraviolet light ($\lambda < 340$ nm), and its photocatalytic efficiency is further limited by a high recombination rate of photogenerated charge carriers and by photocorrosion (Lee and Wu, 2017). Several strategies, such as metal ion loading, transition metal doping, anion doping, dye sensitization, and the formation of composite semiconductors, have therefore been developed to improve the photocatalytic performance of ZnS (Lee and Wu, 2017). In addition to band engineering, the particle size, shape, surface area, crystal structure, and degree of crystallinity also strongly affect the photocatalytic activity (Lee and Wu, 2017).

Among transition metal dopants, Cu is of particular interest. Chauhan et al. (2014) reported that Cu-doped ZnS nanoparticles decolorize methylene blue (MB) much faster than undoped ZnS, especially under visible light, and found the optimum Cu content to be 3 mol%. This shows that Cu incorporation can extend the useful response of ZnS beyond the ultraviolet region.

Besides doping, post-synthesis annealing is a simple and effective way of tuning the properties of ZnS nanoparticles, since it is a common process that reduces material defects and changes the crystallinity and size of the particles (Dwivedi et al., 2021). Dwivedi et al. (2021) observed a red shift in the band gap of Cu-doped ZnS nanoparticles after annealing, and noted that ZnS begins to react with air and convert to ZnO at temperatures above 450 °C. In that study, the samples were prepared by chemical co-precipitation and crystallized in the cubic phase. Therefore, the annealing temperature must be chosen carefully to improve crystallinity without changing the composition of the material.

The properties of the photocatalyst are especially important for the treatment of dye-containing wastewater. Synthetic dyes such as MB are non-degradable, harmful to aquatic life and humans, and a considerable part (about 11–15%) of the dyes used in textile processing is discharged into wastewater (Khan et al., 2024). Photocatalysis has emerged as a promising method for degrading such pollutants, and the morphology of the catalyst, including its surface area, porosity, crystallinity, and particle size, has a significant influence on the degradation efficiency (Khan et al., 2024). For this reason, it is essential to understand how the structural, morphological, and optical properties of a photocatalyst depend on its preparation conditions.

In this study, Cu-doped ZnS nanoparticles were synthesized by the sol–gel method and annealed at 200, 300, and 400 °C. The effect of the annealing temperature on the crystal structure, morphology, and optical properties of the nanoparticles was investigated by X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Vis absorption spectroscopy, respectively. Systematic reports that correlate these properties for sol–gel-derived hexagonal Cu-doped ZnS nanoparticles remain limited. The results provide a basis for future work on the photocatalytic degradation of methylene blue using these nanoparticles.

EXPERIMENTAL

Materials

Zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$, ≥99% purity) and thiourea (CH_4N_2S, ≥99% purity) were used as the zinc and sulfur precursors, respectively. Copper(II) acetate monohydrate ($Cu(CH_3COO)_2 \cdot H_2O$, ≥98% purity) was used as the Cu dopant source. Absolute ethanol was used as the solvent, and monoethanolamine (MEA) was added as a stabilizer. All chemicals were of analytical grade and were used without further purification. Deionized water was used where required.

Synthesis of Cu-Doped ZnS Nanoparticles

Cu-doped ZnS nanoparticles were synthesized by the sol–gel method. First, zinc acetate dihydrate was dissolved in 50 mL of ethanol to obtain a 0.1 M solution, and the solution was stirred magnetically for 30 min at 60 °C. The stabilizer was then added dropwise at a MEA:Zn molar ratio of 1:1, and stirring was continued until a clear, homogeneous solution was obtained. Copper(II) acetate was added to this solution at a doping concentration of 2 at.% relative to Zn.

Separately, thiourea was dissolved in ethanol to obtain a 0.1 M solution, and this solution was added dropwise to the Zn–Cu solution under continuous stirring, keeping the Zn:S molar ratio at 1:1. The resulting mixture was stirred for 2 h at 60 °C to form a stable sol and was then aged for 24 h at room temperature to obtain a gel. The gel was dried at 80 °C for 12 h to remove the solvent and residual organic species, and the dried product was ground into a fine powder using an agate mortar.

The powder was divided into three equal portions, which were annealed at 200, 300, and 400 °C for 2 h in a tube furnace under N_2 atmosphere, using a heating rate of 5 °C/min. The samples were then allowed

to cool naturally to room temperature. The resulting samples are referred to as ZnS:Cu-200, ZnS:Cu-300, and ZnS:Cu-400 according to their annealing temperatures.

Characterization

The crystal structure of the samples was investigated by X-ray diffraction (XRD) using a powder diffractometer with Cu Kα radiation (λ = 1.5406 Å) operated at 40 kV and 30 mA. The patterns were recorded in the 2θ range of 20–80° with a step size of 0.02° and a scan rate of 2°/min. The phases were identified by comparison with the standard JCPDS data, and the average crystallite size was calculated from the Debye–Scherrer equation (Equation 1; Patterson, 1939).

The surface morphology and particle size were examined by scanning electron microscopy (SEM) using a field-emission scanning electron microscope operated at an accelerating voltage of 5 kV. The powder samples were mounted on carbon tape and sputter-coated with a thin gold layer to prevent charging. The particle sizes were estimated from the SEM images using ImageJ software by measuring at least 100 particles for each sample.

The optical properties were studied by UV-Vis absorption spectroscopy using a double-beam spectrophotometer in the wavelength range of 250–800 nm at room temperature. For the measurements, the powders were dispersed in ethanol by ultrasonication for 15 min. The optical band gap was determined from the Tauc plots for direct allowed transitions (Equation 2; Tauc et al., 1966).

RESULTS AND DISCUSSION

Structural Analysis (XRD)

The XRD patterns of the Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C are shown in Figure 1. Eleven diffraction peaks were observed for all samples in the 2θ range of 20–80°. These peaks are located at approximately 26.9°, 28.5°, 30.5°, 39.6°, 47.5°, 51.7°, 55.4°, 56.4°, 57.5°, 58.9°, and 72.8°, and correspond to the (100), (002), (101), (102), (110), (103), (200), (112), (201), (004), and (203) planes of the hexagonal (wurtzite) ZnS phase, respectively. The peak positions are in good agreement with the standard reference data for wurtzite ZnS (JCPDS No. 36-1450), indicating that Cu doping does not alter the hexagonal crystal structure of ZnS.

No additional peaks belonging to Cu-related secondary phases such as CuS, Cu_2S, or CuO were detected in the patterns. This suggests that Cu ions are most likely incorporated into the ZnS lattice rather than forming a separate phase. Since the ionic radius of Cu^{2+} (≈0.73 Å) is very close to that of Zn^{2+} (≈0.74 Å), a substitutional mechanism in which Cu^{2+} replaces Zn^{2+} is expected.

As the annealing temperature increases, the intensity of the peaks increases and their widths decrease. In the sample annealed at 200 °C, the peaks are broad and of low intensity; in particular, the (002) reflection appears only as a weak shoulder between the neighboring (100) and (101) peaks. At 300 °C, the peaks become more distinct, and at 400 °C they are sharp and well resolved. The high-angle (200), (112), (201), and (004) reflections cannot be separated from one another at 200 °C, whereas they can be clearly distinguished at 400 °C. This observation indicates that crystallinity and long-range order improve with increasing annealing temperature.

The crystallite size was estimated from the most intense (100) peak ($2\theta \approx 26.9°$) using the Debye–Scherrer equation (Patterson, 1939):

$$D = 0.9\lambda / (\beta \cos\theta) \qquad (1)$$

where $\lambda = 1.5406$ Å (Cu Kα), β is the full width at half maximum (FWHM) in radians, and θ is the Bragg angle. The approximate FWHM values read from the figure are ≈1.5°, ≈0.9°, and ≈0.6° for the samples annealed at 200, 300, and 400 °C, respectively. Using these values, the average crystallite sizes are found to be approximately 6, 10, and 15 nm. The increase in crystallite size can be attributed to enhanced atomic diffusion during annealing, the coalescence of small particles, and the removal of lattice defects. These results show that all samples remain in the nanometer range, while the crystallite size increases with temperature.

The increase in crystallite size is also consistent with the optical properties. Because the quantum confinement effect weakens as the crystallites grow (Brus, 1984), the optical band gap is expected to decrease with increasing annealing temperature, which agrees with the trend obtained from the UV-Vis analysis.

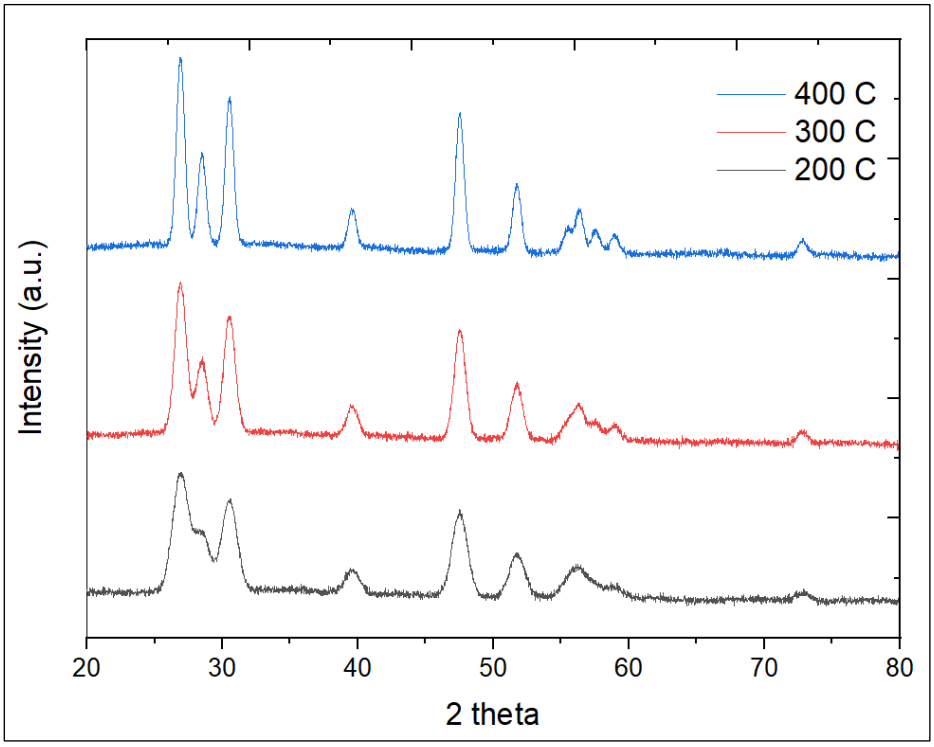


Figure 1. XRD patterns for Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C.

Morphological Analysis (SEM)

Figure 2 presents the SEM images of the Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C, recorded at the same magnification (scale bar: 200 nm). The images show that the annealing temperature strongly affects the particle size, shape, and degree of agglomeration of the samples.

The sample annealed at 200 °C consists of very small, nearly spherical particles with a size of approximately 20–35 nm (average ≈ 28 nm). These particles are strongly agglomerated and form loosely packed, porous, cauliflower-like clusters that reach several hundred nanometers in size. The clusters are separated by numerous voids, and individual particles can still be distinguished within them. This morphology is typical of samples prepared by the sol–gel method at relatively low temperatures, where the high surface energy of the small particles promotes agglomeration.

When the annealing temperature is raised to 300 °C, the particles grow considerably, reaching approximately 60–100 nm (average ≈ 80 nm). The particles retain a rounded shape but have rougher surfaces, and neighboring particles begin to fuse through neck formation. As a result, the structure becomes more compact and the porosity decreases compared with the 200 °C sample, although the agglomerated character is preserved.

At 400 °C, the particles grow further, reaching approximately 150–300 nm (average ≈ 220 nm), and the morphology changes markedly. Large particles with angular, faceted, polyhedral shapes are observed, and many of them are fused into dense, sintered structures with well-defined edges. The formation of such faceted grains indicates enhanced crystal growth and is consistent with the sharper and more intense XRD peaks observed at this temperature. This behavior can be explained by the increase in atomic diffusion at higher temperature, which drives particle coalescence and grain growth to reduce the total surface energy.

The particle sizes estimated from the SEM images (≈ 28, 80, and 220 nm for 200, 300, and 400 °C) are considerably larger than the crystallite sizes calculated from the XRD patterns (≈ 6, 10, and 15 nm). This difference indicates that the particles observed by SEM are not single crystals but polycrystalline aggregates composed of many smaller crystallites. Nevertheless, both techniques show the same trend: the structural coarsening and grain growth increase with the annealing temperature, in agreement with the increased crystallinity observed by XRD and the decrease in the optical band gap discussed in the UV-Vis analysis.

Finally, the transition from small, highly porous agglomerates to large, dense, faceted particles is expected to reduce the specific surface area with increasing temperature. Since surface area and porosity are important for the adsorption of dye molecules, the morphology observed here is likely to influence the photocatalytic degradation of methylene blue, which is planned for future work.

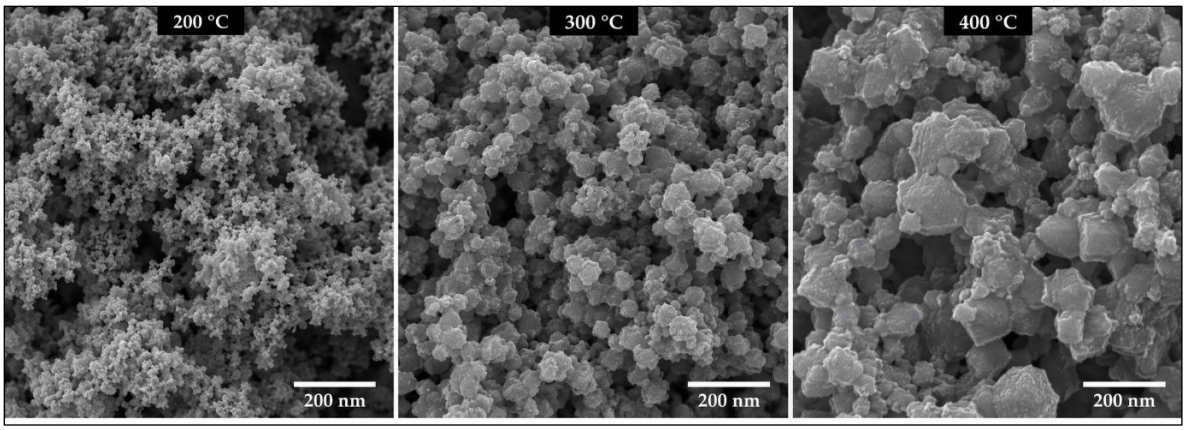


Figure 2. SEM images for Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C.

Optical Analysis (UV-Vis)

Figure 3a shows the UV-Vis absorption spectra of the Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C, and Figure 3b shows the corresponding Tauc plots. All samples exhibit strong absorption in the ultraviolet region, with an absorbance of about 1.2 (a.u.) at 250 nm, followed by a sharp absorption edge and very low absorbance (≈ 0.02–0.05) throughout the visible region up to 800 nm. The steep edge indicates that the absorption originates from direct band-to-band transitions rather than from defect-related absorption tails.

As the annealing temperature increases, the absorption edge shifts systematically toward longer wavelengths (red shift). The edge is located at approximately 343 nm for the sample annealed at 200 °C, 357 nm at 300 °C, and 372 nm at 400 °C, corresponding to a total shift of about 29 nm. This shift indicates a decrease in the optical band gap with increasing annealing temperature.

The optical band gap (E_g) was determined from the Tauc relation (Tauc et al., 1966) for direct allowed transitions:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \qquad (2)$$

where α is the absorption coefficient, $h\nu$ is the photon energy, and A is a constant. E_g was obtained by extrapolating the linear part of the $(\alpha h\nu)^2$ versus $h\nu$ curve to the energy axis (Figure 3b). The band gap values were found to be 3.62 eV for 200 °C, 3.48 eV for 300 °C, and 3.34 eV for 400 °C. These values are consistent with the absorption edges in Figure 3a ($1240/\lambda \approx 3.62$, 3.47, and 3.33 eV, respectively). The band gap decreases by 0.14 eV for each 100 °C increase in annealing temperature, giving a total decrease of 0.28 eV between 200 and 400 °C.

This decrease can be explained by several factors. First, the crystallite size increases from about 6 to 15 nm with annealing temperature, as determined by XRD. As the crystallites grow, the quantum confinement effect weakens and the band gap moves toward that of the bulk material (Brus, 1984). Second, the improved crystallinity and the removal of lattice defects at higher temperatures reduce structural disorder, which narrows the band gap. Third, the incorporation of Cu^{2+} ions into the ZnS lattice introduces Cu 3d states near the top of the valence band, and sp–d exchange interactions between the host band electrons and the localized Cu d electrons can further reduce the band gap. The larger and more crystalline particles observed by SEM at 400 °C are consistent with this trend.

The band gap values obtained here (3.34–3.62 eV) are slightly lower than the values commonly reported for bulk wurtzite ZnS (≈ 3.77 eV; Lee and Wu, 2017), which is attributed to Cu doping. Although the band gap narrows with annealing, all samples still absorb mainly in the UV region and show only weak absorption in the visible range. Nevertheless, the sample annealed at 400 °C, which has the lowest band gap (3.34 eV) and the absorption edge closest to the visible region (372 nm), is expected to utilize light more efficiently than the others. This tunability of the optical properties with annealing temperature is

important for the planned photocatalytic degradation of methylene blue, where both the light absorption and the surface characteristics (discussed in the morphological analysis) are expected to play a role.

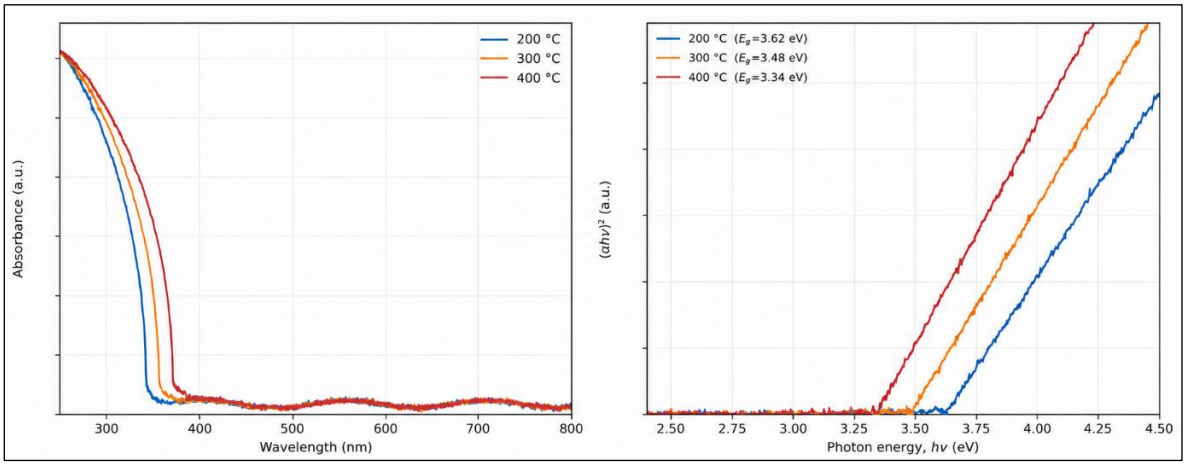


Figure 3. (a) the UV-Vis absorption spectra of the Cu-doped ZnS nanoparticles annealed at 200, 300, and 400 °C. (b) Tauc plot.

CONCLUSION

In this study, Cu-doped ZnS nanoparticles were synthesized by the sol–gel method and annealed at 200, 300, and 400 °C, and the effect of the annealing temperature on their structural, morphological, and optical properties was investigated. XRD analysis showed that all samples crystallized in the hexagonal (wurtzite) ZnS phase without any Cu-related secondary phases, indicating that Cu was incorporated into the ZnS lattice. With increasing annealing temperature, the diffraction peaks became more intense and narrower, and the estimated crystallite size increased from approximately 6 nm to 10 nm and 15 nm. SEM images revealed that the average particle size increased from ≈ 28 nm at 200 °C to ≈ 80 nm at 300 °C and ≈ 220 nm at 400 °C, and that the morphology changed from small, porous agglomerates to large, dense, faceted particles.

The UV-Vis results showed that the absorption edge shifted toward longer wavelengths, from about 343 nm to 372 nm, and that the optical band gap decreased from 3.62 eV to 3.48 eV and 3.34 eV with increasing annealing temperature. This decrease was attributed to the growth of the crystallites, the improved crystallinity, and the incorporation of Cu into the ZnS lattice. These findings show that the annealing temperature is an effective parameter for controlling the structural, morphological, and optical properties of Cu-doped ZnS nanoparticles. At the same time, the increase in particle size at higher temperatures is expected to reduce the surface area, which may affect the dye adsorption. Therefore, the photocatalytic degradation of methylene blue using these samples, which is planned as future work, will make it possible to determine the optimum annealing temperature.

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THE EFFECTS OF TOPOGRAPHIC FACTORS ON SOIL ORGANIC CARBON FRACTIONS AND STABILIZATION MECHANISMS

TOPOĞRAFİK FAKTÖRLERİN TOPRAK ORGANİK KARBON FRAKSİYONLARI VE STABİLİZASYON MEKANİZMALARI ÜZERİNDEKİ ETKİSİ

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ÖZET

Toprak organik karbonu (TOK), toprak kalitesinin korunması ve iklim değişikliğinin hafifletilmesi açısından temel öneme sahiptir. Yüksek dağ ekosistemlerinde, kısa mesafelerde görülen belirgin topoğrafik değişkenlik, karbon girdileri ve karbonun stabilizasyon süreçlerinde önemli farklılıklar oluşturmaktadır. Bununla birlikte, mevcut çalışmaların büyük bölümü toplam TOK ve yüzey topraklarına odaklanmıştır. Bu nedenle topoğrafyanın partikül organik karbon (POC) ve mineral ilişkili organik karbon (MAOC) üzerindeki farklı etkileri henüz yeterince açıklığa kavuşturulamamıştır. Bu derleme; eğim, bakı, yükselti ve topoğrafik konumun POC–MAOC dağılımını hangi fiziksel, hidrolojik ve mineralojik mekanizmalar yoluyla düzenlediğini değerlendirmektedir. 2021–2026 yılları arasında yayımlanan hakemli çalışmalar; topoğrafya, TOK, POC–MAOC, agregat stabilitesi, Fe–Al fazları, toprak derinliği ve redoks koşullarıyla ilişkili anahtar kelimeler kullanılarak taranmıştır. Seçilen literatür, mekanizma temelli bir çerçeve kapsamında sentezlenmiştir. Mevcut bulgular, topoğrafyanın toprak sıcaklığı, nem rejimi, oksijen mevcudiyeti ve materyalin yanal taşınımını birlikte düzenlediğini göstermektedir. POC esas olarak bitkisel kalıntılarla ilişkili olup erozyon, agregat bozulması ve mikroklimatik değişimlere hızlı biçimde yanıt vermektedir. MAOC ise mikrobiyal ürünlerin ve çözünmüş organik bileşiklerin kil mineralleri ile Fe–Al (oksi)hidroksitleri üzerine sorpsiyonu veya birlikte çökelmesi yoluyla oluşabilmektedir. Agregat içi kapanım fiziksel korumayı artırırken, reaktif mineral yüzeyleri kimyasal stabilizasyona katkı sağlamaktadır. Tepe ve yamaç konumlarında erozyon, karbonu ince mineral fraksiyonlarıyla birlikte ortamdan uzaklaştırabilmektedir. Etek konumlarında ise taşınan materyal birikerek gömülebilmektedir. Bununla birlikte, uzun süreli suya doygunluk Fe(III) minerallerinin indirgen çözünmesi yoluyla mineral ilişkili karbonun mobilizasyonuna neden olabilmektedir. Bu nedenle birikim konumları otomatik olarak kalıcı karbon yutakları şeklinde değerlendirilmemelidir. Bütüncül değerlendirmelerde yüzey ve daha derin toprak horizonlarında POC–MAOC fraksiyonları, agregat stabilitesi, reaktif Fe–Al fraksiyonları, tekstür, pH, nem ve redoks koşulları birlikte incelenmelidir. Bu mekanizma temelli yaklaşım, karbon birikimi ile etkin karbon stabilizasyonunun birbirinden ayrılmasını sağlayabilir ve yüksek dağ topraklarının karbon sekestrasyon potansiyelinin daha doğru değerlendirilmesine katkıda bulunabilir.

Anahtar kelimeler: Yüksek dağ ekosistemleri, Topoğrafya, Toprak organik karbonu, POC, MAOC, Fe–Al oksitleri

ABSTRACT

Soil organic carbon (SOC) is essential for maintaining soil quality and mitigating climate change. In high-mountain ecosystems, sharp topographic variation over short distances produces substantial differences in carbon inputs and stabilization processes. Nevertheless, existing studies have largely focused on bulk SOC and surface soils. The contrasting effects of topography on particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) therefore remain insufficiently resolved. This review evaluates the physical, hydrological and mineralogical mechanisms through which slope, aspect, elevation and topographic position regulate POC–MAOC distribution. Peer-reviewed studies published between 2021 and 2026 were screened using keywords related to topography, SOC, POC–

MAOC, aggregate stability, Fe–Al phases, soil depth and redox conditions. The selected literature was synthesized within a mechanism-based framework. Available evidence indicates that topography jointly regulates 1 soil temperature, moisture regime, oxygen availability and lateral material transport. POC is mainly associated with plant residues and responds rapidly to erosion, aggregate disruption and microclimatic change. MAOC can form through the sorption or co-precipitation of microbial products and dissolved organic compounds with clay minerals and Fe–Al (oxyhydr)oxides. Aggregate occlusion promotes physical protection, whereas reactive mineral surfaces contribute to chemical stabilization. At summit and slope positions, erosion may remove carbon together with fine mineral fractions. At footslope positions, transported material may accumulate and become buried. Prolonged water saturation, however, may mobilize mineral-associated carbon through the reductive dissolution of Fe(III) minerals. Depositional positions should therefore not be regarded automatically as persistent carbon sinks. Integrated assessments should examine POC–MAOC, aggregate stability, reactive Fe–Al fractions, texture, pH, moisture and redox conditions in both surface and deeper horizons. This mechanistic approach can distinguish carbon accumulation from effective stabilization and improve assessments of sequestration potential in high-mountain soils.
Keywords: High-mountain ecosystems, Topography, Soil organic carbon, POC, MAOC, Fe–Al oxides

1. GİRİŞ

Toprak, karasal ekosistemlerde karbonun depolandığı başlıca ortamlardan biridir. Toprak organik karbonu (TOK); agregat oluşumu, su tutma kapasitesi, besin elementlerinin döngüsü ve biyolojik etkinlik gibi toprak işlevlerini desteklemektedir. Aynı zamanda atmosfer ile karasal ekosistemler arasındaki karbon alışverişinde önemli bir rol oynamaktadır. Bu nedenle TOK'un korunması, hem toprak kalitesinin sürdürülmesi hem de iklim değişikliğinin sınırlandırılması bakımından önem taşımaktadır. Bununla birlikte topraktaki toplam karbon miktarının yüksek olması, karbonun uzun süre kararlı biçimde tutulduğu anlamına gelmemektedir. Karbonun toprak içindeki fiziksel konumu, mineral yüzeylerle kurduğu ilişkiler ve çevresel değişimlere karşı duyarlılığı da dikkate alınmalıdır (Kleber vd., 2021; Manzoni & Cotrufo, 2024).

Toprak karbonunun miktarı ve korunma biçimi; iklim, bitki örtüsü, ana materyal, toprak özellikleri, arazi kullanımı ve topoğrafyadan birlikte etkilenmektedir. Topoğrafik etkiler özellikle yüksek dağ ekosistemlerinde belirgindir. Bu alanlarda yükselti, eğim, bakı ve topoğrafik pozisyon; kısa mesafelerde sıcaklık, kar örtüsü, güneşlenme, toprak nemi ve bitkisel üretim bakımından önemli farklılıklarla ilişkilidir. Eğim yüzey akışı ile erozyonun şiddetini; bakı enerji ve nem dengesini; yükselti sıcaklık, yağış biçimi ve bitki gelişme dönemini; topoğrafik pozisyon ise su, sediman ve organik madde bakımından kaynak–alıcı ilişkisini etkileyebilmektedir. Dolayısıyla topoğrafyanın TOK üzerindeki etkileri mikroiklim, hidroloji, biyolojik girdiler ve yanal materyal taşınımı aracılığıyla ortaya çıkmaktadır (Che vd., 2021; Dalzell vd., 2022).

Topoğrafya ile TOK arasındaki ilişkiler çoğunlukla toplam karbon miktarı üzerinden incelenmiştir. Ancak toplam TOK ölçümü, farklı oluşum ve korunma mekanizmalarına sahip karbon bileşenlerini birbirinden ayırmamaktadır. Partikül organik karbon (POC), çoğunlukla kısmen ayrışmış bitkisel kalıntılardan oluşmakta ve bitkisel girdiler, erozyon ve agregat bozulması gibi süreçlere görece hızlı yanıt vermektedir. Mineral ilişkili organik karbon (MAOC) ise mikrobiyal ürünlerin ve çözünmüş organik bileşiklerin kil mineralleri ile Fe–Al (oksi)hidroksitleri üzerinde tutulması sonucunda oluşabilmektedir. POC ve MAOC sırasıyla yalnızca kısa ömürlü ve kalıcı karbon havuzları olarak değerlendirilmemelidir. Agregat içine kapanan POC uzun süre korunabilirken redoks değişimleri, desorpsiyon veya mineral çözünmesi MAOC'u yeniden hareketli duruma getirebilmektedir (Rocci vd., 2021; Jilling vd., 2025).

Mevcut literatürde eğim, bakı ve yükseltinin toplam TOK üzerindeki etkileri hakkında önemli bir bilgi birikimi bulunmasına karşın, bu topoğrafik faktörlerin POC ve MAOC'u hangi mekanizmalarla farklılaştırdığı yeterince açıklanamamıştır. Benzer biçimde erozyonla taşınan karbonun hangi bölümünün kaynak yamaçlarda kaybedildiği, hangi bölümünün taban konumlarında gömüldüğü ve biriken karbonun uzun süreli olarak korunup korunmadığı konusunda belirsizlikler bulunmaktadır. Agregat yapısı, reaktif Fe–Al fazları, profil derinliği ve değişken nem–redoks koşullarının topoğrafik gradyanlar boyunca birlikte incelendiği çalışmaların sınırlı olması, yüksek karbon içeriği ile uzun süreli karbon stabilizasyonunun birbirinden ayrılmasını güçleştirmektedir.

Bu çalışma şu sorulara yanıt aramaktadır: (i) eğim, bakı, yükselti ve topoğrafik pozisyon POC ile MAOC'un dağılımını nasıl etkilemektedir; (ii) erozyon, birikme ve agregat dinamikleri karbonun yanal taşınımı ile fiziksel korunmasını nasıl düzenlemektedir; (iii) Fe–Al fazları, toprak nemi ve redoks koşulları mineral ilişkili karbonun oluşumu ve hareketlenmesinde nasıl bir rol oynamaktadır; ve (iv) yüzey toprağına dayalı değerlendirmeler derin horizonlardaki karbon stabilizasyonunu ne ölçüde temsil etmektedir? Bu sorular doğrultusunda çalışmanın amacı, 2021–2026 döneminde yayımlanan literatürü mekanizma temelli olarak incelemek ve topoğrafya–POC–MAOC ilişkilerini agregat yapısı, mineral koruma, profil derinliği, hidrolojik koşullar ve CBS'den türetilen topoğrafik göstergeler çerçevesinde değerlendirmektir. Bu kapsamda mevcut bulguların ortak ve ayrışan yönlerinin, kanıtların sınırlarının ve gelecekteki arazi çalışmalarında ele alınması gereken araştırma gereksinimlerinin belirlenmesi amaçlanmıştır.

2. YÖNTEM

Bu çalışma, anlatısal literatür derlemesi ve kavramsal değerlendirme olarak hazırlanmıştır; arazi örneklemesi, laboratuvar analizi veya özgün deneysel veri içermemektedir.

Literatür taraması, 1 Ocak 2021–29 Eylül 2026 dönemi için yürütülmüştür. Tarama, 29 Eylül 2026 tarihinde güncellenmiştir. ScienceDirect, SpringerLink, Wiley Online Library, Nature Portfolio, Copernicus, Frontiers ve MDPI dergi platformlarındaki hakemli yayınlar incelenmiştir. Gerektiğinde Web of Science ve Scopus kapsamındaki diğer hakemli dergilerde yayımlanan çalışmalar da değerlendirilmiştir. DOI kayıtları, yayıncı sayfaları ve kurumsal kayıtlar üzerinden kaynak künyeleri doğrulanmıştır.

Aramalarda İngilizce anahtar sözcükler kullanılmıştır. Topoğrafya ve ekosistem bağlamı için "soil organic carbon", "topography", "toposequence", "slope", "slope position", "aspect", "elevation", "alpine" ve "high mountain" terimleri kullanılmıştır. Karbon fraksiyonlarına ilişkin aramalarda "particulate organic carbon", "POC", "particulate organic matter", "POM", "mineral-associated organic carbon", "MAOC", "mineral-associated organic matter" ve "MAOM" terimlerine yer verilmiştir. Agregat yapısı ve mineral stabilizasyonu için "aggregate stability", "aggregate-associated carbon", "MWD", "GMD", "iron oxide", "aluminium oxide", "Fe-bound organic carbon", "organo-mineral association" ve "reactive minerals" ifadeleri kullanılmıştır. Profil, hidroloji ve mekânsal analizleri taramak amacıyla "deep soil", "soil horizon", "soil depth", "microbial necromass", "redox", "soil moisture", "reductive dissolution", "digital elevation model", "topographic wetness index", "topographic position index", "remote sensing" ve "digital soil mapping" terimleri aramalara eklenmiştir. Terimler AND ve OR işleçleriyle farklı biçimlerde birleştirilmiştir.

Başlık ve özetler konuya uygunluk bakımından incelenmiştir. Topoğrafik değişkenleri, POC–MAOC fraksiyonlarını, agregat yapısını, Fe–Al fazlarını, nem–redoks koşullarını veya profil derinliğini doğrudan ele alan çalışmalar değerlendirmeye alınmıştır. Hakem değerlendirmesinden geçmemiş metinler ile yalnızca sucul sedimanları konu alan yayınlar kapsam dışında tutulmuştur. Dağ ekosistemlerine ait çalışmalar önceliklendirilmiştir. Bununla birlikte açıklanan mekanizmaların değerlendirilmesi için farklı karasal topraklardan elde edilen bulgular 3 da kullanılmıştır. Güncel tarama dışında kalan kaynaklara yalnızca özgün yöntem tanımları için başvurulmuştur. Fe–Al özütleme yöntemlerinde Mehra & Jackson (2013) ile Parfitt & Childs (1988), agregat yaklaşımında Six vd. (2004) esas alınmıştır.

Çalışma seçimi; platform ve anahtar sözcük taraması, başlık–özet uygunluk değerlendirmesi, tam metnin konu ve mekanizma bakımından incelenmesi ve nihai kaynak kümesinin oluşturulması aşamalarından oluşmuştur. Nihai değerlendirmeye 2021–2026 döneminde yayımlanan 23 yayın ile özgün yöntem tanımları için kullanılan 3 eski kaynak olmak üzere toplam 26 yayın dâhil edilmiştir. Kaynakların çalışma türleri, ekosistemleri, incelenen değişkenleri ve temel bulguları Tablo 1'de sunulmuştur. Tarama anlatısal derleme amacıyla yürütüldüğünden kayıtlar sistematik derleme protokolüne göre ileriye dönük olarak izlenmemiş; yinelenen kayıt ve dışlama sayıları üretilmemiştir. Bu nedenle PRISMA tipi bir akış şeması kullanılmamış ve çalışma sistematik derleme veya meta-analiz olarak sunulmamıştır.

3. BULGULAR VE TARTIŞMA

Bu bölümdeki değerlendirmeler, yayımlanmış çalışmaların ortak ve ayrışan sonuçlarının kavramsal sentezine dayanmaktadır.

3.1 Topoğrafik Faktörler ve Karbonun Yeniden Dağılımı

Dik yamaçlarda yüzey akışı, organik maddece zengin üst toprağı taşıyabilmektedir. POC, POC içeren agregatlar ve ince mineral parçacıklar farklı oranlarda taşınabilir; bu seçici taşınım kaynak yamaçtaki toplam TOK'u ve POC/MAOC oranını değiştirebilir. Agregatların parçalanması mikrobiyal erişimi artırabilirken hızlı gömülme, oksijen erişimini sınırlandırarak taşınan karbonun bir bölümünün korunmasına katkı sağlayabilir. Dolayısıyla kaynak yamaçtaki karbon kaybı, aynı miktarda atmosferik karbon salımı anlamına gelmemektedir. İncelenen erozyon peyzajlarında artan erozyon hızı, toplam TOK ve MAOC stoklarındaki azalmayla ilişkilendirilmiştir. Bir Mollisol havzasında ise kil+silt ve Ca ile ilişkili karbonun MAOC birikimi ve kalıcılığıyla pozitif ilişkili olduğu bildirilmiştir (Dalzell vd., 2022; Hunter vd., 2024; Shi vd., 2024).

Bakı, toprak sıcaklığı ve nemi üzerinden karbon girdisi ile ayrışmayı birlikte etkileyebilmektedir. Kuzey Yarımküre'de kuzeye bakan yamaçlar çoğu zaman daha serin ve nemli koşullar gösterse de enlem, bulutluluk, rüzgârla kar taşınımı ve bitki örtüsü bu örüntüyü değiştirebilir. Yükselti etkisi de doğrusal değildir: düşük sıcaklık ayrışmayı yavaşlatabilirken kısa gelişme dönemi bitkisel girdiyi azaltabilir. Bu nedenle bakı ve yükselti etkileri ana materyal, bitki örtüsü ve topoğrafik pozisyondan bağımsız yorumlanmamalıdır (Che vd., 2021).

Yükselti, sıcaklığın yanı sıra kar örtüsü süresi, donma–çözülme döngüleri ve vejetasyon kuşaklarıyla da ilişkilidir. Donma–çözülme döngüleri agregat kararlılığını azaltarak POC'un mikrobiyal ayrışmaya açılmasına veya ince mineral parçacıklarla birlikte taşınmasına katkı sağlayabilir. Yüksek yükseltilerde düşük ayrışma hızı karbon birikimini destekleyebilir; ancak sınırlı bitki üretimi ve sığ toprak gelişimi bu etkiyi dengeleyebilir. Bu nedenle yükselti boyunca karbon değişimi tek yönlü bir sıcaklık tepkisi olarak değerlendirilmemelidir (Feyissa vd., 2023; Wang vd., 2026).

3.2 CBS Tabanlı Topoğrafik Analiz ve Mekânsal Yorum

CBS, topoğrafya–karbon ilişkilerinin sürekli yüzeyler üzerinde değerlendirilmesine olanak sağlamaktadır. Sayısal yükseklik modelinden (DEM) yükselti, eğim, bakı, plan eğriliği ve profil eğriliği gibi morfometrik değişkenler türetilebilmektedir. Topoğrafik nem indeksi (TWI) suyun birikme eğilimini, topoğrafik pozisyon indeksi (TPI) ise bir hücrenin çevresine göre tepe, yamaç veya çukur konumunu yaklaşık olarak temsil etmektedir. Bu göstergeler arazi gözlemlerinin yerini almamakta, nem, drenaj ve sediman bağlantılılığına ilişkin mekânsal vekiller sağlamaktadır (Radočaj vd., 2024).

Noktasal toprak verileri, DEM türevleri, iklim katmanları ve Sentinel-2 gibi çok bantlı uydu verileriyle birlikte modellenebilmektedir. Regresyon kriging, rastgele orman ve destek vektör regresyonu gibi yaklaşımlar, örneklenmeyen alanlardaki TOK dağılımının tahmininde kullanılmaktadır. Topoğrafik değişkenlerin spektral göstergelerle birlikte kullanılması, özellikle arazi içindeki nem ve taşınım farklılıklarının temsilini geliştirebilir. Bununla birlikte değişkenlerin tahmine katkısı bölgeye ve ölçeğe bağlıdır. Örneğin TWI, su fazlasının görüldüğü zayıf drenajlı alanlarda kurak bölgelerdekinden farklı bir TOK ilişkisi gösterebilir (Cutting vd., 2024).

Mekânsal tahmin ile süreç açıklaması birbirinden ayrılmalıdır. Yüksek model başarısı, topoğrafik değişkenin karbonu doğrudan kontrol ettiğini kanıtlamamaktadır. TWI, TPI veya yükselti; bitki örtüsü, ana materyal, tekstür ve arazi kullanımıyla birlikte değişebilmektedir. Ayrıca rastgele ayrılan eğitim ve doğrulama verileri, mekânsal otokorelasyon nedeniyle model başarısını olduğundan yüksek gösterebilir. Bu nedenle mekânsal çapraz doğrulama kullanılmalı ve model yorumları POC–MAOC, agregat yapısı, Fe–Al fazları ile nem–redoks ölçümleriyle sınanmalıdır. Shapley değerleri gibi açıklanabilir makine öğrenmesi araçları değişkenlerin tahmine katkısını gösterebilir; ancak nedensel mekanizmanın kanıtı değildir (Wadoux vd., 2023).

3.3 POC–MAOC Ayrımı ve Profil Derinliği

POC, düşük yoğunluklu ve çoğunlukla bitkisel kökenli organik parçacıklardan oluşmaktadır. Bu fraksiyon bitki girdisine, erozyona ve agregat bozulmasına görece hızlı tepki vermekte ve mikroorganizmalar için karbon ve enerji kaynağı oluşturmaktadır. Mikrobiyal dönüşüm sonucunda oluşan nekrokütle, MAOC oluşumuna katkı sağlayabilmektedir. İzotopla işaretli bir çayır denemesinde,

eklenen mikrobiyal nekrokütle karbonunun yaklaşık üçte ikisi üç gün içinde ince mineral fraksiyonla ilişkilendirilmiş; bununla birlikte mineral ilişkili nekrokütle karbonunun aylar içinde azalabildiği bildirilmiştir. Bu bulgu, POC'un otomatik olarak geçici, mikrobiyal nekrokütlenin ise otomatik olarak kalıcı bir karbon havuzu şeklinde değerlendirilmemesi gerektiğine işaret etmektedir (Buckeridge vd., 2022; Manzoni & Cotrufo, 2024; Rocci vd., 2021).

MAOC; mikrobiyal ürünlerin, çözünmüş organik bileşiklerin ve küçük bitkisel bileşiklerin mineral yüzeylerde tutulmasıyla oluşabilmektedir. Sorpsiyon, ligand değişimi, katyon köprüleri ve birlikte çökelme başlıca oluşum mekanizmalarıdır. MAOC, ortalama olarak POC'tan daha yavaş dönüşse de mineral ilişki tek başına kalıcılığın kesin göstergesi değildir. Güncel çalışmalar, MAOC içerisinde hızlı dönüşen alt havuzların da bulunabildiğine işaret etmektedir (Jilling vd., 2025; Zhou vd., 2024).

POC ile MAOC arasında tek yönlü ve sabit bir dönüşüm bulunmamaktadır. Bitkisel artıkların parçalanması POC'u oluştururken bu materyalin mikrobiyal kullanımı çözünmüş bileşikler, hücre dışı ürünler ve mikrobiyal nekrokütle üretmektedir. Bu ürünler mineral yüzeylerde tutulduğunda MAOC oluşumuna katkı sağlayabilir. Buna karşılık çözünmüş organik bileşikler mikrobiyal dönüşüm geçirmeden de mineral yüzeylere bağlanabilmektedir. Literatürde bu yollar sırasıyla canlı-içi (in vivo) ve canlı-dışı (ex vivo) oluşum yolları olarak ele alınmaktadır. Bu yolların göreli önemi; artık kalitesine, mikrobiyal etkinliğe, kil içeriğine ve reaktif mineral yüzeylerin bulunabilirliğine bağlıdır (Manzoni & Cotrufo, 2024).

Yüzey toprağı, güncel bitki girdisinin yüksek olması nedeniyle POC bakımından zengin olabilmektedir. Derin horizonlarda organik girdi genellikle azalmaktadır. Buna karşılık çözünmüş karbon taşınımı, derin kökler ve karbonca doymamış mineral yüzeyler önem kazanmaktadır. Bu nedenle MAOC'un toplam TOK içindeki payı derinlikle artabilmektedir. Ancak söz konusu artış, yüzey POC'unun doğrudan MAOC'a dönüştüğünü kanıtlamamaktadır. Profil karşılaştırmalarında sayısal derinlikten çok pedojenik horizonlar dikkate alınmalıdır. Hacim ağırlığı, taşlılık ve gömülü yüzeyler de değerlendirmeye alınmalıdır (Wang vd., 2022).

Derin horizonlardaki düşük karbon derişimi, bu katmanların karbon bütçesindeki önemini azaltmamaktadır. Derin toprakların yüksek kütlesi, düşük derişimlerin önemli stoklara karşılık gelmesini sağlayabilmektedir. Ayrıca derinlikteki mineraller yüzey horizonlarına göre daha düşük organik karbon yüküne sahip olabilir ve yeni karbon için bağlanma alanları sunabilir.

Buna karşılık sınırlı mikrobiyal enerji arzı ve düşük kök girdisi, bu kapasitenin kullanılmasını kısıtlayabilir. Bu nedenle derin topraklardaki karbon tutulma potansiyeli yalnızca mineral kapasiteyle değil, karbonun bu yüzeylere ulaşabilirliğiyle birlikte değerlendirilmelidir (Wang vd., 2022).

3.4 Agregat Yapısı ve Fiziksel Koruma

Makroagregatlar genellikle 250 μm'den büyük yapısal birimler olarak tanımlanırken mikroagregatlar daha küçük boyut sınıflarını temsil etmektedir; ancak operasyonel boyut sınırları kullanılan yönteme göre değişebilmektedir. Organik parçacıklar makroagregat oluşumu için çekirdek sağlayabilir. Makroagregatlar içinde gelişen mikroagregatlar, oksijen ve enzim erişimini sınırlandırarak organik karbonun fiziksel korunmasına katkıda bulunabilir. Buna karşılık ıslanma–kuruma, donma–çözülme ve yüzey akışı agregatların parçalanmasına neden olabilmektedir (Six vd., 2004; Wu vd., 2023).

Agregat koruması, karbonun yalnızca agregat içinde bulunmasına indirgenmemelidir. Serbest POC bitkisel girdileri ve parçalanmayı daha doğrudan yansıtırken agregat içi POC fiziksel erişim kısıtı altında kalabilmektedir. Mikroagregatlar içinde mineral yüzeylerle temas eden bileşikler ise fiziksel ve kimyasal korumadan birlikte yararlanabilir. Bu nedenle agregatların parçalanması bütün karbon havuzlarını aynı ölçüde etkilememektedir. Önceden kapalı olan POC hızla erişilebilir duruma gelebilirken mineral yüzeylere bağlı karbonun serbest kalması ek desorpsiyon veya mineral çözünmesi süreçlerini gerektirebilir. Erozyona uğrayan Mollisol yamaçlarında yapılan bir çalışmada, birikim konumundaki makroagregatların belirli bitkisel kökenli karbonu seçici olarak koruduğu ve erozyon–birikme süreçlerinin agregat içi karbonun kimyasal bileşimiyle ilişkili olduğu bildirilmiştir (Six vd., 2004; Wang vd., 2024; Wu vd., 2023).

Ortalama ağırlık çapı (MWD) ve geometrik ortalama çap (GMD), agregat boyut dağılımı ile suya dayanıklılığın değerlendirilmesinde kullanılmaktadır. Ancak bu göstergeler karbon yaşını veya MAOC miktarını doğrudan açıklamamaktadır. Sonuçlar örnek hazırlama, ıslatma ve eleme enerjisine duyarlı olduğundan aynı protokol kullanılmalı; MWD ve GMD, serbest POC, agregat içi POC ve agregat boyut sınıflarındaki MAOC ile birlikte yorumlanmalıdır (Six vd., 2004).

3.5 Fe–Al Fazları ve Pedoklimatik Kontroller

Fe ve Al (oksi)hidroksitleri, yüksek yüzey reaktiviteleri nedeniyle MAOC oluşumunda önem taşımaktadır. Ditionit–sitrat–bikarbonatla özütlenen Fed, pedojenik serbest Fe oksitlerinin büyük bölümünü kapsamaktadır. Bu fraksiyon, iyi kristallenmiş ve düşük kristallenme derecesine sahip fazları içerebilmektedir. Bu nedenle Fe_d yalnızca kristalin Fe olarak tanımlanmamalıdır. Asit amonyum oksalatla özütlenen Fe_o ve Al_o ise daha reaktif ve kısa menzilli düzenli fazların yaklaşık göstergeleri olarak kullanılmaktadır. Fe_o/Fe_d oranı, göreli kristallenme derecesinin değerlendirilmesine katkı sağlamaktadır. Yüksek bir oran, tek başına yüksek karbon kalıcılığının kanıtı olarak kabul edilmemelidir (Mehra & Jackson, 2013; Parfitt & Childs, 1988).

Kısa menzilli düzenli Fe–Al fazları, yüksek özgül yüzey alanları ve reaktif hidroksil grupları nedeniyle organik bileşikleri güçlü biçimde tutabilmektedir. Daha iyi kristallenmiş Fe oksitleri de organik karbonla ilişki kurmakla birlikte yüzey alanı ve bağlanma bölgeleri mineral türüne göre değişmektedir (Schweizer vd., 2021). Organik bileşikler mineral yüzeyine adsorbe olabileceği gibi Fe veya Al ile birlikte çökelebilir. Birlikte çökelme, organik karbonun oluşan mineral yapıya veya düzensiz yüzeylere dâhil olmasına katkı sağlayabilir. Sphagnum sulak alanlarında yapılan geniş ölçekli bir karşılaştırmada, bitkinin asidik ve fenolik ürünleri ile reaktif Fe–Al fazlarındaki artış arasında ilişki kurulmuş; metal bağlı karbonun MAOC birikimiyle ilişkili olduğu bildirilmiştir (Zhao vd., 2023). Bu nedenle toplam Fe miktarı yerine Fe fazının kristallenme derecesi, yüzey reaktivitesi ve organik maddeyle birlikteliği değerlendirilmelidir

Pirofosfatla özütlenen Fe_p ve Al_p, organik bileşiklerle kompleksleşmiş metal fraksiyonları için yöntemsel göstergelerdir. Pirofosfat bazı inorganik fazları da etkileyebilmektedir. Bu nedenle söz konusu fraksiyonlar, belirli bir bağ türünün doğrudan ölçümü olarak değerlendirilmemelidir. Seçici özütleme sonuçları mineralojik ve spektroskopik yöntemlerle desteklenmelidir (Parfitt & Childs, 1988).

Toprak nemi, redoks koşulları üzerinden Fe aracılı karbon stabilizasyonunu etkileyebilmektedir. Orta düzeyde nem; bitki üretimini, mikrobiyal dönüşümü ve MAOC öncüllerinin oluşumunu destekleyebilir. Suya doygunluk ise oksijen difüzyonunu sınırlandırır; Fe(III)'ün indirgenmesi Fe oksitlerini çözebilir ve ilişkili karbonu hareketlendirebilir. Drenaj sonrasında Fe(II)'nin yeniden yükseltgenmesi yeni reaktif yüzeyler oluşturabilir; organik karbon bu yüzeylerde tutulabilir veya Fe ile birlikte çökelebilir. Bu nedenle değişken su tablasına sahip taban topraklarında Fe–karbon ilişkisi mevsimsel olarak değişebilmektedir (Giannetta vd., 2022; Jia vd., 2024).

Redoks salınımlarının net etkisi süreçlerin zamanlamasına bağlıdır. İndirgenme sırasında Fe ile birlikte çözünen karbon gözenek suyunda kalabilir, mikrobiyal olarak kullanılabilir veya yanal akışla taşınabilir. Yeniden yükseltgenme hızlı gerçekleşirse yeni oluşan Fe fazları bu karbonun bir bölümünü tekrar tutabilir. Karbon sistemden uzaklaşmışsa aynı mineral yenilenmesi net bir stabilizasyon sağlamayabilir. Al fazları Fe gibi redoks tepkimesi göstermese de pH ve kompleksleşme koşullarındaki değişimlerden etkilenmektedir. Bu farklılık, Fe ve Al fraksiyonlarının ayrı değerlendirilmesini gerekli kılmaktadır (Giannetta vd., 2022; Jia vd., 2024).

pH; mineral yüzey yükünü, Al çözünürlüğünü ve mikrobiyal etkinliği etkilemektedir. Kil içeriği ise mineral yüzey alanını ve su tutma kapasitesini artırabilmektedir. Ancak kil yüzdesi tek başına MAOC kapasitesini açıklamaz; kil minerali türü, Fe–Al kaplamaları, özgül yüzey alanı ve mevcut karbon doygunluğu da dikkate alınmalıdır (Jia vd., 2024; Kleber vd., 2021). Topoğrafik konum ile tekstür birlikte değişebildiğinden istatistiksel modellerde bu etkilerin ayrıştırılması gerekmektedir.

3.6 Mekanistik sentez ve bilgi boşlukları

Literatür, topoğrafik etkilerin ardışık ve karşılıklı etkileşimli süreçler üzerinden ortaya çıktığına işaret etmektedir. Topoğrafya mikroiklim ve hidrolojiyle birlikte değişmekte; bu koşullar erozyon, birikme, agregat yapısı ve mineral reaktivitesini etkileyebilmektedir. Söz konusu süreçler POC–MAOC dağılımına ve karbonun kalıcılığına katkıda bulunmaktadır. Bununla birlikte ilişkiler doğrusal olmamakla birlikte bitki örtüsü, ana materyal, toprak yaşı ile arazi kullanımı tarafından değiştirilebilmektedir (Che vd., 2021; Dalzell vd., 2022; Giannetta vd., 2022).

Tepe konumlarında iyi drenaj ve sınırlı yukarı yamaç katkısı baskın olabilmektedir. Bitkisel girdiler yüzeyde POC oluşumunu desteklerken erozyon, POC'u ve ince mineral parçacıkları sistemden uzaklaştırabilir. Mineral yüzeylerin karbonla düşük doygunluğu yeni MAOC oluşumu için kapasite sağlayabilse de düşük nem veya sınırlı mikrobiyal dönüşüm bu kapasitenin kullanılmasını kısıtlayabilir.

Bu nedenle tepe konumundaki düşük toplam TOK yalnızca hızlı ayrışmayla açıklanmamalıdır (Che vd., 2021; Feyissa vd., 2023).

Yamaç konumları taşınma, geçici depolanma ve yeniden aşınmanın birlikte gerçekleşebildiği geçiş alanlarıdır. Agregatların taşınma sırasında parçalanması POC'u ayrışmaya açabilir; ince mineral parçacıklarla temas ise çözünmüş ve mikrobiyal kökenli karbonun tutulmasına katkı sağlayabilir. Net sonuç eğim uzunluğuna, yüzey örtüsüne, akışın sürekliliğine ve sedimanın arazide kalma süresine bağlıdır. Bu nedenle yamaç ortasındaki tek bir örnekleme noktası dinamik yamaç süreçlerini yeterince temsil etmeyebilir (Dalzell vd., 2022).

Taban konumlarında sediman birikimi, POC'un gömülmesine ve MAOC taşıyan ince fraksiyonların yoğunlaşmasına katkı sağlayabilir. Yüksek nem, oksijen kısıtı yoluyla mineralizasyonu yavaşlatabilir; ancak uzun süreli suya doygunluk Fe oksitlerinin indirgen çözünmesini ve ilişkili karbonun hareketlenmesini artırabilir. Dönemsel kuruma ise yeni Fe fazlarının oluş masına ve karbonun yeniden tutulmasına olanak verebilir. Bu nedenle taban konumlarının karbon sekestrasyon potansiyeli, yalnızca depolanan karbon miktarına değil; birikme, ayrışma, çözünme ve dışa taşınma akılarının dengesine bağlıdır (Giannetta vd., 2022; Jia vd., 2024).

Başlıca bilgi boşluğu, POC–MAOC fraksiyonları ile agregat sınıflarının aynı topoğrafik dizi üzerinde birlikte incelendiği çalışmaların azlığıdır. Benzer biçimde Fe_d–Fe_o–Fe_p, Al_d– Al_o–Al_p ve sürekli nem–redoks verileri çoğu çalışmada bütünleştirilmemektedir. Tek zamanlı örnekleme; kar erimesi, yaz kuraklığı ve değişken su tablasının etkilerini açıklamakta yetersiz kalmaktadır. Yüzey toprağına dayalı çalışmalar, derin horizonlardaki mineral koruma kapasitesini gözden kaçırabilir. Birikim alanındaki yüksek TOK değeri ise yerinde stabilizasyon ile yukarı yamaçtan taşınan karbonun ayrılmasına tek başına olanak vermeyebilir. Bir karst yamaç çalışmasında, yamaç konumu boyunca partikül organik madde (POM), mineral ilişkili organik madde (MAOM), mikrobiyal nekrokütle, lignin belirteçleri ve değişebilir Fe birlikte değerlendirilmiştir; ancak benzer bütünleşik tasarımlar yüksek dağ sistemlerinde hâlen sınırlıdır. Gelecek çalışmalarda profil ve yamaç ölçeğinde karbon kütle dengelerinin kurulması gerekmektedir (Wang vd., 2022; Zou vd., 2026).

3.7 İncelenen Çalışmaların Genel Özellikleri ve Temel Bulguları

Tablo 1, değerlendirmeye alınan çalışmaların genel özelliklerini ve temel bulgularını karşılaştırmalı olarak göstermektedir. Derleme, meta-analiz ve yöntem makalelerinde tek bir çalışma alanı veya standart örnekleme derinliği bulunmadığından ilgili hücrelerde bu durum belirtilmiştir. Bulgular, kaynaklarda incelenen koşullar ve raporlanan ilişkilerle sınırlandırılmıştır

Tablo 1: İncelenen Çalışmaların Genel Özellikleri ve Temel Bulguları

Çalışma Alanı / Ekosistem	Topoğrafik Faktör	Toprak Derinliği	Karbon Fraksiyonu	Diğer Temel Parametreler	Temel Bulgu	Kaynak ve Yıl
Kuzeybatı İngiltere tarımsal çayırları	–	0–10 cm (0–5 ve 5–10 cm; ayrıca 10–20 cm)	Mikrobiyal nekrokütle ve MAOM	13C/15N, mikrobiyal biyokütle, ince mineral fraksiyonu	İşaretli nekrotik C'nin yaklaşık üçte ikisi üç içinde mineral fraksiyonla ilişkilense de mineral ilişkili C sekiz ay içinde azalmıştır.	Buckeridge vd. 2022
Alpin çayır toprağı	Yükselti, bakı	A ve B horizonları	TOK ve Al/Fe ilişkili C	pH, Fe/Al seçici özütlemeleri, bitki ve iklim değişkenleri	İncelenen gradyanda yükselti ve bakı, Al–Fe fazlarıyla ilişkili TOK dağılımındaki farklılıklarla ilişkilendirilmiştir.	Che vd. 2021
Yağışlı tarım arazileri	TWI ve diğer DEM türevleri	0–10 cm	TOK	Sentinel-2, rastgele orman, destek vektör regresyonu, nem verileri	TWI çoğu modelde önemli bir değişken olmuş; çalışma	Cutting vd. 2024

					alanında TOK ile negatif ilişki göstermiştir.	
Erozyona açık tarımsal peyzaj	Yamaç konumu, erozyon, birikme	0-150 cm	TOK	DEM, arazi kullanımı, sediment yeniden dağılımı	Topoğrafya ve arazi kullanımı TOK tahminine katkı sağlamış; aşağı yamaçta birikmesi karbonun kısmen korunmasıyla ilişkilendirilmiştir.	Dalzell vd. 2022
Güneybatı Çin alpin orman ve çayırları	Yükselti	0–10 ve 10–20 cm	TOK ve stabilizasyon göstergeleri	Bitki örtüsü, iklim, toprak özellikleri	Karbon miktarı ve potansiyel stabilizasyon mekanizmaları yükselti ve ekosistem tipine göre farklılaşmıştır.	Feyissa vd. 2023
Ilıman hidromorfik ve çeltik toprakları	Hidrolojik konum, redoks rejimi	Elüviyal üst horizon ve illüviyal alt horizon	TOK ve Fe ilişkili C	Fe türleşmesi, X-ışını soğurma spektroskopisi, mikroagregatlar, redoks	Redoks çevrimleri Fe dönüşümleri ve mikroagregat içi/dışı C dağılımındaki değişimlerle ilişkilendirilmiştir.	Giannetta vd. 2022
Oregon Coast Range, ormanlı erozyon peyzajı	Erozyon hızı, tepe konveksliği	0-140 cm	TOK, POC ve MAOC	Δ14C, tekstür, toprak kalınlığı, ışık algılama ve uzaklık ölçme	İncelenen 16 alanda modellenen erozyon hızı arttıkça toplam TOK ve MAOC stokları üstel olarak azalmıştır.	Hunter vd. 2024
Küresel veri sentezi	İklim, ekosistem ve derinlik kovaryatları	0–30 cm	TOK ve Fe ilişkili organik C	Fe_o, Fe_d, Fe_p, Al fraksiyonları	Fe oksit stokları ve Fe ilişkili organik C ekosistemler arasında değişmiş; düşük kristalli Fe–Al göstergeleri TOK ile güçlü ilişki göstermiştir.	Jia vd. 2024
Çoklu ekosistem kapsamlı derleme	–	–	MAOM	Desorpsiyon, inkübasyon, izotop çalışmaları	MAOM'un tamamının yavaş çevrimli olmadığı ve hızlı çevrimli alt havuzlar içerebildiği bildirilmiştir.	Jilling vd. 2025
Mekanistik derleme	–	–	Mineral ilişkili organik madde/C	Mineral yüzey kimyası, sorpsiyon, mikrobiyal süreçler	Mineral–organik arayüzün statik bir kaplama değil, dinamik ve heterojen bir sistem olduğu vurgulanmıştır.	Kleber vd. 2021
36 izleme çalışmasının veri–model sentezi	–	–	POM ve MAOM	C/N, kil, artık kalitesi, modelleme	Veri setinde MAOM oluşumu çoğunlukla mikrobiyal nekrokütle yoluyla açıklanmış; bu yolun önemi kil	Manzoni & Cotrufo 2024

					ve C/N bağlamına göre değişmiştir.	
Yöntem çalışması	–	–	–	Ditionit–sitrat–bikarbonat ile serbest Fe oksitlerinin özütlenmesi	Yöntemin Fe oksitlerini uzaklaştırma ve ölçme temeli tanımlanmıştır.	Mehra & Jackson 2013
Yöntemsel derleme ve karşılaştırma	–	–	Dolaylı TOK ilişkisi	Fe_d, Fe_o, Fe_p ve Al karşılıkları	Seçici özütlemelerin operasyonel fraksiyonlar olduğu ve mineralojik yorum gerektirdiği belirtilmiştir.	Parfitt & Childs 1988
Dijital TOK haritalama derlemesi	DEM türevleri	–	TOK	Uzaktan algılama, iklim, topoğrafya, makine öğrenmesi	Açık uzaktan algılama ve topoğrafya verilerinin TOK haritalamada yararlı olduğu, performansın ölçek ve çevreye bağlı kaldığı bildirilmiştir.	Radočaj vd. 2024
Küresel meta analiz	İklimsel değişim bağlamı	–	POM/POC ve MAOM/MAOC	Isınma, yağış, CO_2, N girdisi	Toplam TOK tepkisinin POM ve MAOM arasındaki dağılıma bağlı olduğu bildirilmiştir.	Rocci vd. 2021
Tarımsal toposekans	Yamaç ve toposekans konumu	0–20 cm	TOK ve mineral ilişkili C	Kil, özgül mineral yüzey alanı, mineralojik özellikler	TOK depolanması kil yüzdesinden çok mineral yüzey alanı ve toposekans boyunca değişen mineral özelliklerle ilişkilendirilmiştir.	Schweizer vd. 2021
Erozyon birikim gösteren Mollisol havzası	Erozyon ve birikme konumu	0–20 ve 60–80 cm	MAOC; Ca-, Fe/Al- ve kil-silt ilişkili organik C	Özgül yüzey alanı, adsorpsiyon, mineral fraksiyonları	Çalışma koşullarında Ca ve kil-silt ilişkili organik C, MAOC kalıcılığı ve birikimiyle pozitif ilişkili bulunmuştur.	Shi vd. 2024
Agregat literatürü derlemesi	–	–	Agregat ilişkili C, POM	Makro/mikroagregat, biyota, bozunma	Mikroagregat oluşumu ve agregat içi kapanmanın organik madde korunmasındaki rolü sentezlenmiştir.	Six vd. 2004
Fransa ulusal TOK veri seti	Topoğrafya kovaryatları	0–50 cm	TOK stoku	Shapley değerleri, iklim, bitki, toprak, makine öğrenmesi	Bitki örtüsü ve topoğrafya tahminlerde önemli bulunmuş; Shapley değerlerinin nedensellik değil, model katkısı	Wadoux vd. 2023

					sunduğu vurgulanmıştır.	
Havza ölçeği	Havza konumu ve profil derinliği	0–100 cm	TOK	Tekstür, pH, hacim ağırlığı, arazi kullanımı	TOK'u açıklayan etmenlerin derinlikle değiştiği ve yüzey sonuçlarının alt toprağa genellenemeyeceği bildirilmiştir.	Wang, L. vd. 2022
Alpin ekosistemler	İklim ve alpin çevre gradyanları	0–10, 10–20 ve 20–40 cm	POC ve MAOC	İklim duyarlılığı, sürekli depolama göstergeleri	İncelenen alpin sistemlerde TOK dinamiklerinin büyük bölümü POC'un iklim duyarlılığı ve birikimiyle ilişkilendirilmiştir.	Wang, Y. vd. 2026
Erozyona uğrayan Mollisol tarım peyzajı	Erozyon ve birikme konumu	0–20 ve 80–100 cm	Agregat ilişkili organik C	Agregat boyutu, 13C nükleer manyetik rezonans, bitki kökeni	Birikim konumundaki makroagregatlarda belirli C3 kökenli C'nin seçici olarak korunduğu ve erozyonun agregat içi organik C bileşimiyle ilişkili olduğu bildirilmiştir.	Wang, Z. vd. 2024
Helan Dağları yükselti gradyanı	Yükselti	0–20 ve 20–40 cm	Agregat ilişkili C	Agregat boyutu, enzimler, mantar/bakteri oranı	Agregat ilişkili C yükseltiyle artmış; fiziksel koruma göstergeleri yanal yönde doğrusal artış göstermiştir.	Wu vd. 2023
Çin sulak alanları ve küresel karşılaştırma	Sulak alan/depresyon bağlamı; Sphagnum gradyanı	0–25 cm	POC, MAOC, metal bağlı organik C	Fe_o, Fe_d, Al_p, pH, kil	Sphagnum alanlarında reaktif Fe–Al ve metal bağlı organik C daha yüksek bulunmuş; MAOC incelenen aralıkta TOK ile doğrusal ilişki göstermiştir.	Zhao vd. 2023
8341 gözlemli küresel sentez	Yükselti, eğim, iklim kovaryatları	–	POC ve MAOC	pH, kil-silt, iklim, derinlik, modelleme	POC ve MAOC'un küresel dağılımı ile dönüş süreleri farklı çevresel değişkenlerle ilişkilendirilmiştir.	Zhou vd. 2024
Guangxi karst tepesiz havza sistemi	Yamaç konumu	Yüzey toprağı	POM ve MAOM	Mikrobiyal nekrokütle, lignin fenolleri, değişebilir Fe/Ca, 13C nükleer manyetik rezonans	İncelenen yamaçta POM ve MAOM'un kaynakları ve kimyasal konuma göre farklılaşmış; fungal nekrokütlenin her iki fraksiyona katkı sağladığı bildirilmiştir.	Zou vd. 2026

4. SONUÇ ve ÖNERİLER

İncelenen literatür, topoğrafyanın yüksek dağ topraklarındaki TOK dağılımını tek başına belirleyen bir değişken olmadığını; mikroiklim, hidroloji ve yanal materyal taşınımı aracılığıyla etkili olduğunu göstermektedir. Eğim erozyon ve birikme süreçleriyle, bakı enerji ve nem dengesiyle, yükselti sıcaklık ve bitki gelişme dönemiyle, topoğrafik pozisyon ise kaynak–alıcı ilişkileriyle bağlantılıdır. Bununla birlikte bu ilişkiler doğrudan POC veya MAOC değişiminin kanıtı değildir; agregat yapısı, tekstür, mineral yüzey özellikleri ve redoks koşulları temel aracı değişkenlerdir.

POC güncel bitkisel girdilere ve fiziksel bozulmaya görece hızlı yanıt verirken agregat oluşumu ve mikrobiyal dönüşüm süreçlerine de katkı sağlamaktadır. MAOC çoğunlukla daha uzun dönüş süreleriyle ilişkilendirilse de mineral ilişki kalıcılığı garanti etmemektedir. Özellikle indirgen koşullarda Fe oksitlerinin çözünmesi, desorpsiyon ve kök kaynaklı bileşikler mineral ilişkili karbonu yeniden hareketlendirebilir. Benzer biçimde taban konumlarındaki POC gömülmesi ve ince mineral birikimi karbon stokunu artırabilir; ancak yüksek stok, uzun süreli stabilizasyon veya net sekestrasyonla eşdeğer değildir.

Mevcut kanıtların önemli bir bölümü yüzey toprağına ve tek zamanlı örneklemeye dayandığından, topoğrafik konumların uzun süreli karbon dengesi üzerindeki etkisi belirsizliğini korumaktadır. Gelecekteki çalışmalarda yüzey ve derin horizonlardaki toplam TOK, serbest ve agregat içi POC, MAOC, MWD/GMD, tekstür, hacim ağırlığı ve taşlılık birlikte değerlendirilmelidir. Fed, Feo, Fep, Ald, Alo ve Alp fraksiyonları pH ve kil minerolojisiyle birlikte yorumlanmalı; sürekli nem, sıcaklık, redoks potansiyeli ve su tablası ölçümleri tek zamanlı örneklemeyi tamamlamalıdır. Erozyon ve birikme akılarının karbon bütçesine dâhil edilmesi, yüksek karbon içeriği ile uzun süreli karbon stabilizasyonunun birbirinden ayrılmasına katkı sağlayacaktır.

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GIS-BASED ASSESSMENT OF SOIL EROSION RISK IN BAYBURT PROVINCE USING THE ICONA MODEL

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Abstract
Soil erosion is a major land-degradation process that threatens the sustainability of soil resources and reduces land productivity. In this study, the ICONA erosion-risk model was applied within a Geographic Information Systems (GIS) environment to determine the spatial distribution of erosion risk in Bayburt Province. Slope, geology, land use, and land cover, which are key factors influencing erosion processes, were evaluated within the model framework. Slope values derived from a Digital Elevation Model were classified into five classes, while geological units were categorized according to their lithological characteristics and susceptibility to erosion. Slope and geology were integrated using the ICONA evaluation matrix to generate the potential erosion map. Based on CORINE land-cover classes, vegetation cover was grouped into four density classes (<25%, 25-50%, 50-75%, and >75%). Land-use classes were adapted to the categories defined in the ICONA model and evaluated together with vegetation cover to generate the soil-protection map. The potential erosion and soil-protection layers were then integrated using the ICONA matrix to produce the final erosion-risk map. The results showed that 11.25% of the study area was classified as very low risk, 17.40% as low risk, 23.13% as moderate risk, 32.50% as high risk, and 15.72% as very high risk. High and very high risk areas together accounted for 48.22% of the study area, indicating that nearly half of the province is susceptible to erosion. The findings highlight the need to incorporate erosion susceptibility into land-use planning and to develop appropriate soil-conservation practices, particularly in high-risk areas. Integrating the ICONA model with GIS provides a practical approach for spatial erosion-risk assessment and for identifying priority areas for soil conservation and sustainable land management.
Keywords: ICONA, soil erosion, erosion risk, Geographic Information Systems, land use.

INTRODUCTION

Soil is a fundamental natural resource for sustaining agricultural production and maintaining ecosystem functions, and it plays a key role in sustainable environmental management (Doran & Parkin, 1994). Soil degradation is defined as the decline or loss of soil functions and is recognized as a major environmental problem threatening the sustainability of terrestrial ecosystems (Oldeman, 1997; Jie et al., 2002; Yücesoy & Edis, 2025).

Soil erosion is one of the major causes of soil degradation. The removal of topsoil rich in organic matter and nutrients reduces soil quality and fertility and consequently has adverse effects on agricultural production (Lal, 1998; García-Ruiz et al., 2015; Parlak et al., 2022). In addition, soil erosion negatively affects ecosystem integrity and biodiversity (Pimentel & Burgess, 2013; Asuoha et al., 2019; Firoozi & Firoozi, 2024). The fact that soil loss by erosion greatly exceeds the rate of soil formation through natural processes further emphasizes the severity of this problem (Verheijen et al., 2009).

Soil erosion is one of the major environmental problems in Türkiye. Approximately 86% of the country's soils are reported to be affected by erosion at varying degrees of severity, while 20.6% are classified as having moderate or higher erosion risk (Erpul et al., 2020). Türkiye's topographic structure,

climatic conditions, and inappropriate land-use practices are among the main factors that intensify erosion (Kılıç, 2022).

Because erosion results from the interaction of several environmental factors, spatial assessment methods are important for identifying erosion-prone areas. In this context, GIS-based erosion models are widely used not only to determine the spatial distribution of erosion risk but also to support the planning of soil management and conservation practices (Panagos et al., 2015). Among these models, ICONA enables the integration of key factors affecting erosion processes, including geology, slope, land use, and vegetation cover density, within a GIS environment (Everest et al., 2025). Owing to its limited data requirements and practical structure, the model can be used to identify the spatial distribution of erosion-susceptible areas (Yücesoy & Edis, 2025; Şeker et al., 2026). These characteristics make ICONA particularly suitable for erosion-risk assessment over large areas.

In this study, the ICONA model was implemented in a GIS environment to determine the spatial distribution of soil erosion risk within Bayburt Province. Slope, geology, land use, and land cover characteristics were evaluated together to reveal the spatial pattern of erosion risk. The main objectives were to determine the distribution of different erosion-risk classes across the province, identify areas with high and very high risk, and contribute to the identification of priority areas for soil conservation practices. The results are expected to provide a scientific basis for sustainable land management and soil conservation activities in Bayburt Province.

MATERIALS AND METHODS

General characteristics of the study area

Bayburt Province is located in the eastern part of the Black Sea Region of Türkiye and is bordered by Trabzon to the north, Erzincan to the south, Gümüşhane to the west, and Erzurum to the east. The study area covers the entire administrative boundary of Bayburt Province and has an area of approximately 371,136 ha. Elevation ranges from 1,390 to 3,357 m above sea level, with a mean elevation of approximately 1,550 m (Anonymous, 2026a). The mean annual precipitation of the province is 450.1 mm (Anonymous, 2026b). The location map of the study area is presented in Figure 1.

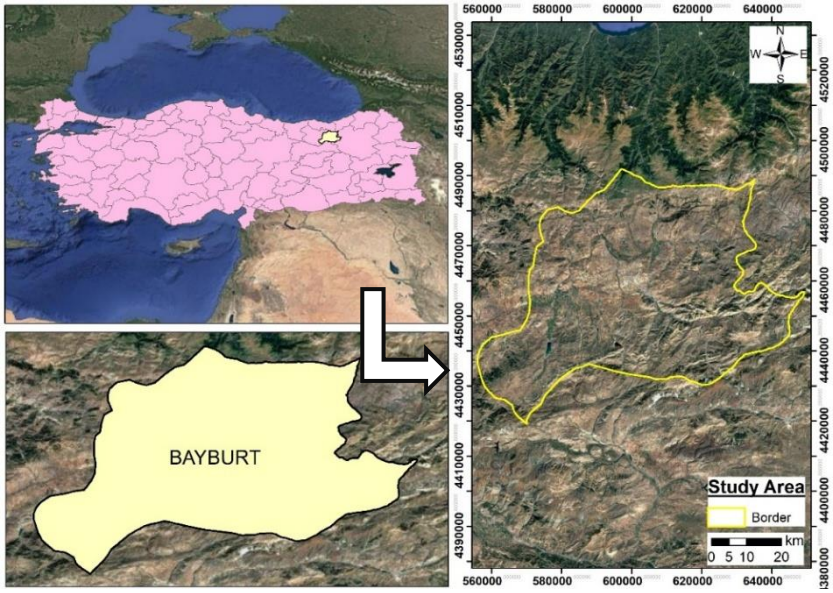


Figure 1. Location map of the study area

Slope, geology, land use capability (LCC), and land cover data were used as the primary input datasets for implementing the ICONA model. These datasets were processed in ArcGIS 10.8.2 to generate potential and actual erosion-risk maps. The methodological workflow and analysis stages followed in the study are presented in Figure 2.

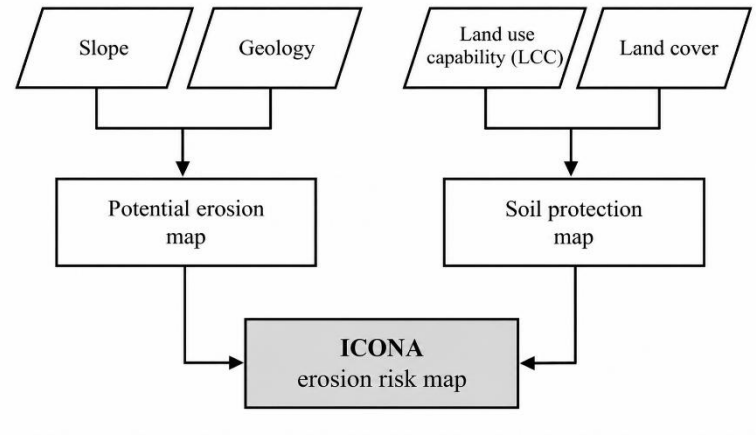


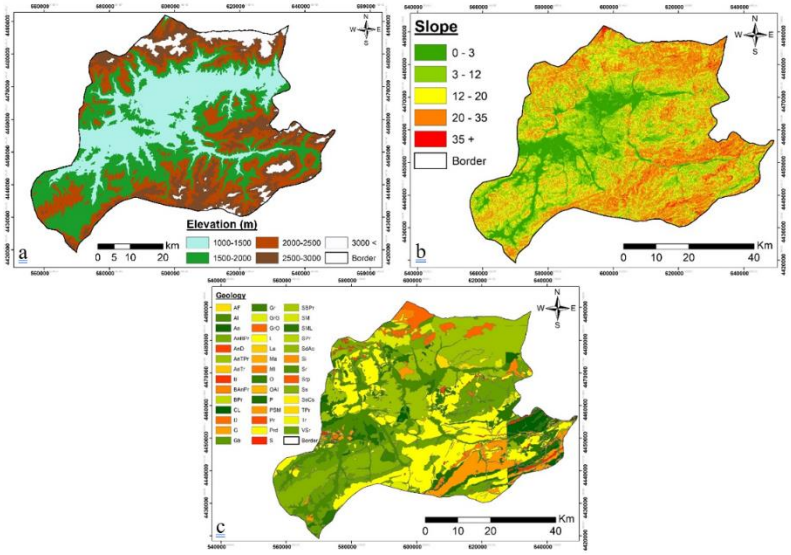
Figure 2. Workflow of the ICONA erosion model

RESULTS AND DISCUSSION

Bayburt Province has a highly rugged and mountainous topography. Elevation exceeds 2,000 m particularly in the northern and southern parts of the study area, while high and very high slope values occur across a substantial portion of the province (Figure 3a,b). This topographic setting is an important factor influencing surface runoff and erosion processes within the study area.

In terms of lithology, the study area is mainly characterized by limestone (22%), andesite (20%), volcanic-sedimentary rocks (15%), and conglomerate (8%) (Figure 3c). With respect to land use capability, Class VII and VIII lands are widely distributed throughout the study area. When considered together with the topographic and lithological characteristics, these features constitute important environmental factors controlling the spatial variation in erosion susceptibility.

The spatial distribution of land use capability classes shows that Class VII and VIII lands occupy extensive areas and are widely distributed across different parts of the study area. In contrast, Class I, II, and III lands occur in more limited and fragmented areas. Overall, lands with relatively high agricultural capability (Classes I-IV) are limited, whereas lands with greater land-use restrictions (Classes VI-VIII) are more widespread (Figure 4a). The rugged and mountainous topography of Bayburt, the extensive occurrence of steep slopes, its lithological characteristics, and the predominance of Class VII and VIII lands are therefore considered important factors influencing the spatial distribution of high erosion risk.



Gr: Granite; GrG: Granite–Granodiorite; GrO: Granitoid; G: Gypsum; CL: Clayey Limestone; L: Limestone; S: Sandstone; SM: Sandstone–Mudstone; SML: Sandstone–Mudstone–Limestone; Ml: Mélange; Ma: Marble; O: Olistostrome; Prd: Peridotite; Pr: Pyroclastic Rock; Srp: Serpentinite; Si:

Siltstone; SBPr: Spilite–Basalt–Pyroclastic Rock; SPr: Spilite–Pyroclastic Rock; Ss: Schist; SsCs: Schist–Calcschist; Tr: Travertine; TPr: Tuff–Pyroclastic Rock; VSr: Volcanic–Sedimentary Rock; SdAc: Slope Debris–Alluvial Cone.

Figure 3. Elevation (a), slope (b), and geology (c) maps.

The areal distribution of land cover and land-use classes indicates that most of the study area consists of forest and semi-natural areas. This class accounts for 91.50% of the total area, whereas agricultural areas represent 6.59%. Artificial surfaces cover 1.70% of the study area, while water bodies have the smallest share at 0.21% (Figure 4b). These results show that natural and semi-natural land cover is clearly dominant, whereas agricultural and artificial land uses are more limited. Spatially, the land-cover classes display a fragmented and heterogeneous pattern across the study area (Figure 4b). The areal and proportional distribution of land-cover classes is presented in Table 1.

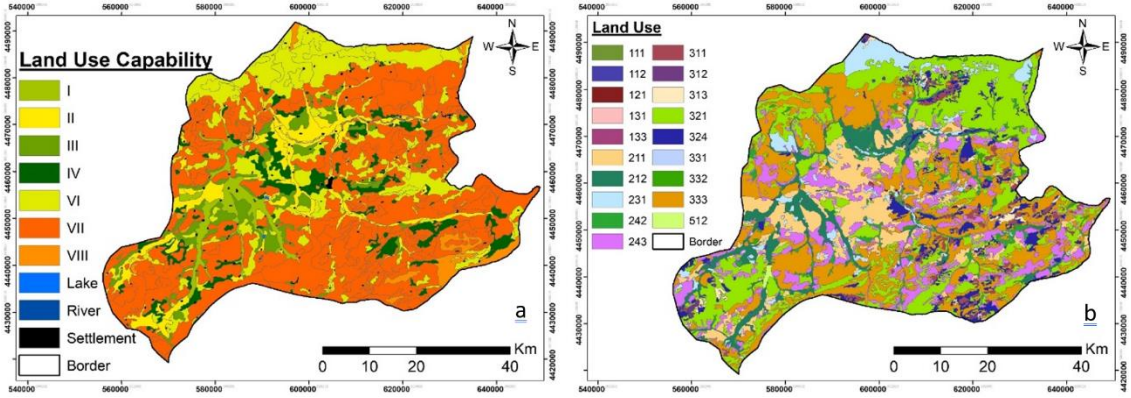


Figure 4. Land use capability (a) and land use (b) maps.

Table 1. Distribution of land-cover classes in the study area.

Land-cover classes	Area (ha)	Proportion (%)
1. Artificial surfaces	6,309.31	1.70
2. Agricultural areas	24,457.86	6.59
3. Forest and semi-natural areas	339,626.55	91.50
5. Water bodies	742.27	0.21
TOTAL	371,136.00	100.00

The vegetation cover-density classes indicate that most of the study area (90.96%) falls within the 50-75% cover class. Areas with 25-50% vegetation cover account for 4.63%, while areas with less than 25% cover represent 3.19%. Forest areas with the highest vegetation cover (>75%) constitute the smallest share, at 1.22% (Table 2). This distribution was considered an important component in determining the soil-protection level within the ICONA model.

Table 2. Distribution of vegetation cover-density classes in the study area.

Vegetation cover density	Cover type	Area (ha)	Vegetation cover (%)
<25%	Built-up, bare, or very sparsely vegetated areas	11,839.24	3.19
25-50%	Non-irrigated agricultural areas and rangelands	17,183.60	4.63
50-75%	Agricultural and natural areas expected to have more continuous/dense vegetation cover	337,636.19	90.96
>75%	Forest areas	4,527.86	1.22
	TOTAL	371,186.89	100.00

The potential erosion distribution obtained by jointly evaluating slope and geology is presented in Figure 5a, while the final ICONA erosion-risk map, generated after incorporating the soil-protection level, is shown in Figure 5b.

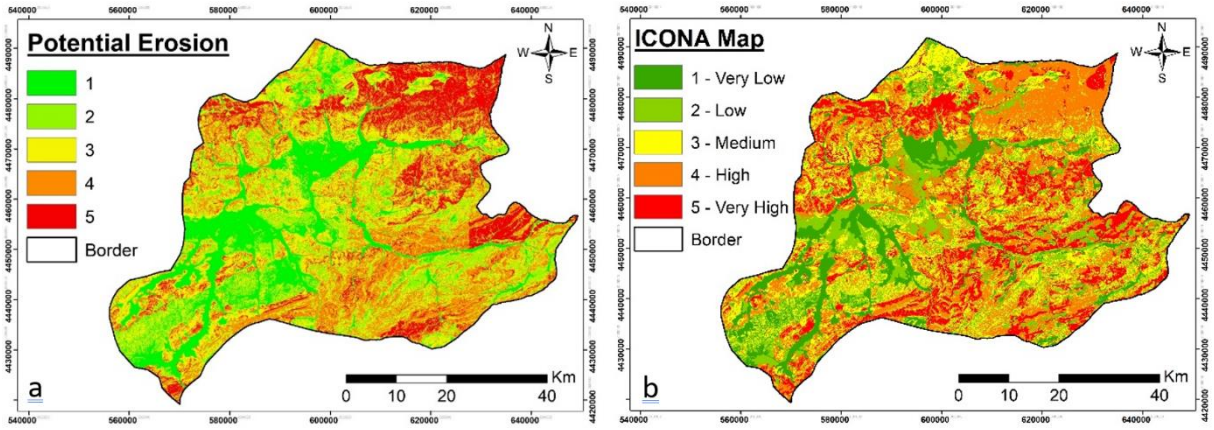


Figure 5. Potential erosion risk (a) and ICONA erosion-risk (b) maps.

The spatial distribution of erosion-risk classes according to the ICONA model shows that areas with high and very high erosion risk are concentrated particularly in the northern, northeastern, eastern, and southeastern parts of the study area, while they occur in a more fragmented pattern elsewhere. The general correspondence of these areas with steep and rugged terrain indicates that topography has an important influence on increasing erosion risk. In contrast, areas with very low and low erosion risk form broader and more continuous zones in the central and southwestern parts of the study area, which may be associated with the relatively gentler topographic conditions in these locations. The areal and proportional distributions of the ICONA erosion-risk classes are presented in Table 3. Şeker et al. (2026) evaluated erosion risk using the ICONA model in a micro-watershed in Rize and reported that high-risk areas were concentrated particularly where steep slopes, erosion-susceptible lithology, and sparse vegetation occurred. Dutal (2026) reported that areas with high and very high erosion susceptibility in Geben Valley National Park accounted for 29.17% and 48.88%, respectively.

Table 3. Areal and proportional distribution of ICONA erosion-risk classes

Class value	Erosion class	Area (ha)	Proportion (%)
1	Very Low	41,752.80	11.25
2	Low	64,577.66	17.40
3	Moderate	85,843.76	23.13
4	High	120,619.20	32.50
5	Very High	58,342.58	15.72
	TOTAL	371,136.00	100.00

The distribution of erosion-risk classes showed that 120,619.20 ha (32.50%) of the study area was classified as high risk and 58,342.58 ha (15.72%) as very high risk. Together, these two classes covered 178,961.78 ha (48.22%) of the study area. The moderate-risk class covered 85,843.76 ha (23.13%), whereas the low and very low risk classes together accounted for 106,330.46 ha (28.65%). These findings indicate that erosion risk is substantial across a considerable portion of the study area. Yücesoy and Edis (2025) reported that high and very high erosion-risk classes in the Terme Stream Watershed accounted for 32.2% and 35.6%, respectively. In a study conducted in the southwestern part of the Biga Peninsula using the ICONA model, Everest et al. (2025) classified 42.32% of the area as moderate risk, 21.82% as high risk, and 2.35% as very high risk. They also reported that high-risk areas were particularly associated with steep slopes and sparse vegetation cover.

CONCLUSION

In this study, the current status of soil erosion risk in Bayburt Province was evaluated using the ICONA model. The results showed that erosion risk varies considerably across the province and becomes pronounced in certain areas. In particular, the fact that high and very high risk classes together cover approximately half of the study area indicates that erosion is an important land-management issue in the region.

The distribution of high-risk areas indicates a close relationship between land characteristics and erosion risk. Therefore, erosion control should involve not only identifying existing risk but also developing

land-use practices compatible with the natural characteristics of the terrain. In high-risk areas, maintaining existing vegetation cover, adopting practices that reduce surface runoff and soil loss, and incorporating erosion risk into land-use decisions are particularly important.

The ICONA model enabled different land characteristics to be evaluated jointly within a GIS environment and facilitated the identification of priority areas for erosion control. The resulting maps can provide a useful basis for soil conservation and land-use planning in Bayburt. Future studies incorporating field observations and more detailed spatial datasets could further support model validation and contribute to more robust conservation decisions at the local scale.

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FUNGAL DISEASES OF TOMATO (SOLANUM LYCOPERSİCUM L.): MAJOR PATHOGENS, SYMPTOMS AND MANAGEMENT STRATEGIES

DOMATESİN (SOLANUM LYCOPERSICUM L.) FUNGAL HASTALIKLARI: BAŞLICA PATOJENLER, BELİRTİLER VE MÜCADELE STRATEJİLERİ

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Abstract
Tomato (*Solanum lycopersicum* L.) is the second most important vegetable crop worldwide after potato and is a key source of income and nutrition, particularly for smallholder farmers in tropical and subtropical regions. However, tomato production is severely constrained by a wide range of foliar, stem, fruit and soil-borne diseases caused mainly by fungal and fungal-like pathogens. Warm, humid and fluctuating climatic conditions favour the onset and rapid spread of these diseases, leading to substantial yield and quality losses and consequent economic damage. The most important diseases include seedling damping-off, Septoria leaf spot, early blight, late blight, anthracnose, powdery mildew, southern blight, Fusarium wilt, Verticillium wilt and buckeye rot. This review synthesizes current knowledge on these major tomato diseases, focusing on their causal agents, symptomatology and epidemiology, together with their agronomic and economic significance. For each disease, the main diagnostic symptoms and available management options are summarized, including cultural practices, use of resistant cultivars, seed and soil treatments, biological control and rational fungicide applications within an integrated disease management framework. By combining information from published literature and practical field experience, this review aims to provide a concise reference for researchers, extension specialists and growers seeking to improve sustainable disease management in tomato production systems
Keywords: Tomato, Fungal diseases, Control methods, IPM

Özet
Domates (*Solanum lycopersicum* L.), dünya genelinde patatesten sonra en önemli ikinci sebze ürünü olup özellikle tropikal ve subtropikal bölgelerdeki küçük ölçekli üreticiler için önemli bir gelir ve besin kaynağıdır. Bununla birlikte domates üretimi, başta fungal ve fungus benzeri patojenlerin neden olduğu yaprak, gövde, meyve ve toprak kökenli çok sayıda hastalık tarafından ciddi biçimde sınırlandırılmaktadır. Sıcak, nemli ve değişken iklim koşulları, bu hastalıkların ortaya çıkmasını ve hızla yayılmasını kolaylaştırarak önemli verim ve kalite kayıplarına, dolayısıyla ekonomik zararlara yol açmaktadır. Başlıca hastalıklar arasında fide çökerteni, Septorya yaprak lekesi, erken yanıklık, geç yanıklık antraknoz, külleme, güney yanıklığı, Fusarium solgunluğu, Verticillium solgunluğu ve meyvelerde görülen Phytophthora çürüklüğü yer almaktadır. Bu derlemede, domatesin söz konusu önemli hastalıklarına ilişkin güncel bilgiler; hastalık etmenleri, belirtileri ve epidemiyolojilerinin yanı sıra tarımsal ve ekonomik önemleri bakımından ele alınmaktadır. Her hastalık için tanıda kullanılan başlıca belirtiler ve mevcut mücadele seçenekleri özetlenmekte; kültürel uygulamalar, dayanıklı çeşit kullanımı, tohum ve toprak uygulamaları, biyolojik mücadele ve akılcı fungisit kullanımı entegre hastalık yönetimi çerçevesinde değerlendirilmektedir. Yayımlanmış literatürden elde edilen bilgiler ile uygulamaya yönelik saha deneyimlerini bir araya getiren bu derleme, domates üretim sistemlerinde sürdürülebilir hastalık yönetimini geliştirmeyi amaçlayan araştırmacılar, tarımsal yayım uzmanları ve üreticiler için özlü bir başvuru kaynağı sunmayı hedeflemektedir.
Anahtar kelimeler: Domates, fungal hastalıklar, mücadele yöntemleri, entegre mücadele.

GİRİŞ

Domates üretiminde hastalıkların etkisi yalnızca bitki ölümüyle sınırlı değildir. Yaprak alanının azalması fotosentetik kapasiteyi düşürürken, kök ve iletim dokularının zarar görmesi su ve besin maddesi alımını sınırlandırmaktadır. Meyve enfeksiyonları ise ürünün doğrudan pazarlanabilirliğini azaltmaktadır. Hastalık nedeniyle yaprak örtüsünü kaybeden bitkilerde meyvelerin güneş yanıklığına açık hale gelmesi, primer enfeksiyonların dolaylı kalite kayıpları da oluşturabileceğini göstermektedir (UC IPM, t.y., 2013c, 2013a, 2023).

Açık alan ve örtü altı yetiştiriciliğinde hastalık baskısı aynı değildir. Yağış ve sıçrayan suyla yayılan etmenler açık alanda öne çıkarken, seralarda uzun üretim dönemi, bitki yoğunluğu ve nem yönetimi önem kazanmaktadır. Toprakta kalıcı yapılar oluşturan patojenler ise ardışık yetiştiricilik dönemleri arasında inokulumun korunmasına neden olmaktadır. Bu nedenle farklı üretim bölgelerinde hazırlanmış mücadele programlarının yerel koşullara uyarlanmadan kullanılması uygun değildir (UC IPM, t.y., 2013h, 2013e, 2013l).

Funguslar ile oomyceteler arasında biyolojik ve taksonomik farklılıklar bulunmaktadır. *Alternaria, Septoria, Colletotrichum* ve *Fusarium* gerçek funguslar içerisinde yer alırken, *Phytophthora* ve *Pythium* geleneksel anlamda fungus benzeri organizmalar olarak adlandırılan oomycetelerdir (Kamoun ve ark., 2015). Bu ayrım, yalnızca terminolojik değildir; etmenlerin enfeksiyon biyolojisini ve mücadelede seçilecek aktif maddelerin etkinlik spektrumunu da ilgilendirir. Bütün domates hastalıklarını sıcak ve nemli koşullarla açıklamak da yetersizdir. Örneğin *Fusarium* solgunluğu ile Verticillium solgunluğu farklı sıcaklık eğilimleri gösterirken, külleme gelişimi uzun süreli serbest yaprak suyuna bağlı değildir (UC IPM, 2013h, 2013e, 2013l; FRAC, 2026).

Bu derlemenin amacı, seçilmiş önemli hastalıkların tanısı ile mücadele kararları arasındaki bağlantıyı ortaya koymak ve araştırıcılar, yayım uzmanları ve üreticiler için kullanılabilir bir başvuru metni sunmaktır. Hastalıklar; belirtileri sıralanan bağımsız sorunlar olarak değil, ortak inokulum kaynakları ve yetiştiricilik uygulamaları üzerinden etkileşen bir üretim sistemi içinde değerlendirilmiştir.

YÖNTEM

Çalışma, erişilebilir hakemli araştırmalar ile üniversitelerin bitki patolojisi ve entegre mücadele yayınlarının birlikte değerlendirildiği anlatısal bir derlemedir. Eylül 2026 itibarıyla doğrulanabilen kaynaklardan yararlanılmıştır. Tür adlarının açıklanmasında taksonomik araştırmalar, mücadele etkinliğinin tartışılmasında ise deneysel çalışmalar esas alınmıştır. Kurumsal yayım kaynakları, belirtilerin tanımlanması ve yetiştiricilik önlemlerinin açıklanmasında kullanılmıştır. Makale künyeleri ve DOI eşleşmeleri 11 Eylül 2026 tarihinde Crossref ve Europe PMC kayıtları üzerinden kontrol edilmiştir. Kurumsal kaynakların başlıkları ve güncelleme bilgileri ilgili resmî sayfalardan doğrulanmıştır. Çalışma bir sistematik derleme veya meta-analiz değildir; araştırmalar arasında birleşik etki büyüklüğü hesaplanmamıştır.

Ana kapsam, öz bölümünde belirtilen on hastalık grubudur. *Fusarium* kök ve kök boğazı çürüklüğü, solgunluk hastalığından ayrılması amacıyla ayrıca açıklanmıştır. Domateste görülen kurşuni küf, yaprak küfü, beyaz çürüklük ve diğer fungal hastalıklar bu kapsamın dışında bırakılmıştır. Farklı ülkelerdeki fungisit listeleri, Türkiye için ruhsatlı kullanım önerisi olarak aktarılmamıştır.

Başlıca hastalıklar

Fide çökerteni

Çökerten, tek bir etmenin oluşturduğu özgül bir hastalıktan çok, çıkış öncesi veya çıkış sonrası fide ölümlerini kapsayan bir hastalık grubudur. Domateste başlıca *Pythium* spp., *Phytophthora* spp. ve *Rhizoctonia* spp. ile ilişkilidir. Çıkış öncesinde tohum veya genç fide toprak altında çürür ve üretim alanında düzensiz çıkış görülür. Çıkış sonrasında ise gövdenin toprak seviyesinde koyulaşması, incelmesi ve dayanıklılığını kaybetmesi sonucunda fide devrilir (UC IPM, 2013b).

Yetersiz drenaj, sıkışmış veya aşırı ıslak yetiştirme ortamı enfeksiyon riskini artırmaktadır. Etmenlere göre sıcaklık gereksinimi değiştiğinden bütün çökerten vakaları yalnızca serin koşullara bağlanmamalıdır. Sağlıklı tohum ve fide, temiz viyol ve uygun yetiştirme ortamı kullanımı önceliklidir. Sulama, kök bölgesinde uzun süreli su doygunluğu oluşturmayacak şekilde düzenlenmelidir. Tohum uygulamalarının seçimi, saptanan etmenin fungus veya oomycete oluşuna göre yapılmalıdır. Fide kaybının önlenmesi, yeniden dikim maliyetinin ve üretim takvimindeki gecikmenin azaltılması bakımından önemlidir (UC IPM, 2013b, 2013i).

Septoria yaprak lekesi

Septoria lycopersici tarafından oluşturulan hastalık genellikle alt yapraklardan başlayarak üst yapraklara ilerlemektedir. Küçük, dairesel, açık kahverengi veya gri merkezli ve koyu kenarlı lekeler tipiktir. Lekelerin merkezinde görülen siyah noktacıklar, fungusun piknitleridir. Leke sayısı arttığında yapraklar sararır, nekroze olur ve işlevini kaybeder. Meyve enfeksiyonu seyrektir; başlıca ekonomik etki yaprak alanının azalması üzerinden ortaya çıkar (Meadows ve ark., 2021).

Etmen, bulaşık bitki artıkları ve bazı Solanaceae konukçuları üzerinde varlığını sürdürebilir. Yağmur sıçraması, ıslak yapraklarla temas eden işçiler ve ekipman sporların yayılmasına katkı sağlamaktadır. Yaprak ıslaklığının azaltılması, malçlama, bitkilerin desteklenmesi ve bulaşık artıkların yönetimi mücadeleyi destekler. Erken yanıklıkta görülen daha büyük ve belirgin halkalı lekelerden farklı olarak, *Septoria* lekeleri çoğunlukla küçük ve piknitlidir. Ancak karışık enfeksiyonlarda yalnızca leke görünümüne dayanmak yeterli olmayabilir. Koruyucu uygulamalar, sağlıklı yaprakların enfeksiyonunu sınırlandırmayı hedeflemeli; mevcut nekrozların iyileşmesi beklenmemelidir (Meadows ve ark., 2021).

Erken yanıklık

Domateste erken yanıklık, klasik kaynaklarda çoğunlukla *Alternaria solani* ile ilişkilendirilmiştir. Bununla birlikte büyük sporlu *Alternaria* türlerinin çok lokuslu değerlendirilmesi, domatesle ilişkili bazı etmenlerin *A. linariae* altında ele alınmasını sağlamıştır. *A. tomatophila* bu adın sinonimleri arasındadır. Eski kayıtların tamamının yeni bir ad altında otomatik olarak birleştirilmesi yerine, izolatların tanısında kullanılan yöntemlerin dikkate alınması gerekir (Woudenberg ve ark., 2014; Meadows ve ark., 2025).

Belirtiler çoğunlukla yaşlı yapraklarda başlayan kahverengi-siyah lekeler ve leke içindeki konsantrik halkalarla tanınmaktadır. Çevre dokuda sararma ve ilerleyen dönemde yaprak kaybı görülür. Meyvede, özellikle sap bağlantısı çevresinde koyu renkli, çökük ve derimsi lezyonlar gelişebilir. Etmen bulaşık artıklarda korunur; konidiler hava hareketleri ve sıçrayan suyla yayılır. Yaprak yüzeyindeki nem ve bitkinin fizyolojik durumu enfeksiyon gelişimini etkiler (Meadows ve ark., 2025; UC IPM, 2013c).

Mücadelede dengeli besleme, bitki artıklarının yönetimi, kendiliğinden çıkan domates ve patates bitkilerinin uzaklaştırılması, uygun münavebe ve yaprak ıslaklığını azaltan uygulamalar birlikte kullanılmalıdır. Çeşitler arasındaki duyarlılık farkları yararlı olmakla birlikte, tolerans ifadesi bağışıklık anlamına gelmez. Fungisit programı, hastalık riski ve yerel duyarlılık verileriyle ilişkilendirilmelidir. Ticari ürün adını değiştirmek, aktif maddeler aynı etki mekanizmasındaysa etkili bir direnç yönetimi sağlamaz (Meadows ve ark., 2025; UC IPM, 2013c; FRAC, 2026).

Geç yanıklık

Geç yanıklık, *Phytophthora infestans* tarafından oluşturulan ve uygun koşullarda hızla ilerleyen bir oomycete hastalığıdır. Yapraklarda başlangıçta suda haşlanmış görünümlü, düzensiz lekeler oluşur; bunlar kısa sürede genişleyerek kahverengi nekrozlara dönüşür. Nemli koşullarda yaprak alt yüzeyinde, lezyonun ilerleyen kenarında beyazımsı sporulasyon görülebilir. Yaprak sapı ve gövde enfeksiyonlarına, meyvede genellikle sertliğini başlangıçta koruyan kahverengi lezyonlar eşlik edebilir (UC IPM, 2013f). Yüksek nemin ılıman sıcaklıklarla uzun süre birlikte görülmesi epidemiyi desteklemektedir. Bulaşık fideler, çevredeki enfekteli konukçular ve hava yoluyla taşınan inokulum dikkate alınmalıdır. Geç yanıklığın yönetimi, hastalıksız fide kullanımı, çevredeki inokulum kaynaklarının azaltılması ve sık gözlemle başlamaktadır. Duyarlılığı daha düşük çeşitlerin kullanımı korumayı güçlendirebilir; ancak etmen popülasyonunun özellikleri önemlidir. Kimyasal koruma gerektiğinde oomycetelere etkili ve hedef kullanım için ruhsatlı ürünler seçilmeli, uygulama zamanı enfeksiyon riskiyle ilişkilendirilmelidir (UC IPM, 2013f; FRAC, 2026).

Antraknoz

Domates antraknozunun önemli etmenlerinden biri *Colletotrichum coccodes*'tir. Hastalık özellikle olgun ve aşırı olgun meyvelerde belirginleşmektedir. Dairesel, çökük lekeler zamanla genişler; yüzeyde koyu renkli yapılar ve nemli koşullarda somon renkli spor kitleleri görülebilir. Aynı etmen köklerde siyah noktacıklarla karakterize çürüklük oluşturabilmektedir. Dolayısıyla meyve enfeksiyonu ile kök kolonizasyonu aynı üretim alanında birlikte değerlendirilebilir (UC IPM, 2013a).

Meyve lekeleri, ürünün görünümünü ve depolama dayanıklılığını etkileyerek doğrudan ayıklama kaybına neden olur. Hasadın geciktirilmemesi, hastalıklı meyvelerin ayrılması ve meyvelerin ıslak toprakla temasının azaltılması yararlıdır. Olgunlaşma döneminde yağmurlama sulamanın sınırlandırılması ve Solanaceae dışındaki uygun bitkilerle münavebe inokulum yönetimini desteklemektedir. Hastalık baskısı ve yetiştirme koşulları değerlendirilmeden her üretim sistemi için zorunlu bir fungisit programı öngörülmemelidir (UC IPM, 2013a).

Külleme

Domateste külleme birden fazla etmenle ilişkilidir. *Leveillula taurica* enfeksiyonlarında yapraklarda düzensiz sarı alanlar ve ilerleyen dönemde nekroz görülmektedir. Beyaz sporulasyon, yaprakların alt veya üst yüzeyinde belirginleşebilir. Örtü altı üretiminde önemli olan ve yayım kaynaklarında *Oidium*

neolycopersici adıyla yer alan etmen ise yaprak yüzeyinde belirgin beyaz, unumsu koloniler oluşturmaktadır. Bu farklı görünümler nedeniyle bütün külleme enfeksiyonlarında aynı belirti dağılımı beklenmemelidir (UC IPM, 2023, 2013h).
Konidiler hava hareketleriyle yayılır. Külleme, uzun süreli serbest su gereksinimi bakımından birçok yaprak lekesi hastalığından ayrılır; yaprakların kuru görünmesi enfeksiyon riskinin olmadığı anlamına gelmez. Yaprak nekrozu ve işlev kaybı, meyvelerde güneş yanıklığı ve kalite azalmasına katkı sağlayabilir. Seralarda düzenli gözlem, dengeli bitki gelişimi ve uygun havalandırma temel önlemlerdir. Gerektiğinde erken dönemde uygulanan ruhsatlı fungisitler veya biyolojik ürünler programı destekleyebilir. Kükürt içeren ürünlerde sıcaklığa ve yağ uygulamalarıyla aralığa ilişkin etiket koşulları özellikle dikkate alınmalıdır (UC IPM, 2023, 2013h).

Fusarium solgunluğu
Fusarium solgunluğunun etmeni *Fusarium oxysporum* f. sp. *lycopersici*'dir. Köklerden giren etmen ksilemi kolonize eder. Alt yapraklarda sararma, bazen bitkinin yalnızca bir tarafında belirginleşen solgunluk ve gövde boyunca ilerleyebilen iletim demeti kahverengileşmesi tipiktir. Belirtiler, bitkinin su gereksiniminin arttığı meyve gelişimi döneminde daha belirgin hale gelebilir (UC IPM, 2013e).
Etmen toprakta uzun süre canlı kalabilmekte; bulaşık fide, toprak, ekipman ve bazı durumlarda tohumla taşınabilmektedir. Hastalık genellikle sıcak koşullarda öne çıkmaktadır. Mücadelede çeşidin yalnızca "*Fusarium* dayanıklı" olarak tanımlanması yeterli değildir. Konukçu dayanıklılığını aşma yeteneği bakımından tanımlanan üç temel ırka karşı çeşit veya anacın reaksiyonu ayrı değerlendirilmelidir. Belirli bir ırka dayanıklılık, diğer ırklara dayanıklılığı zorunlu kılmaz (UC IPM, 2013e; Stokes ve ark., 2026).
Dayanıklı çeşit veya anaç, temiz fide, bulaşık toprağın taşınmasının önlenmesi ve inokulum azaltıcı uygulamalar programın temelini oluşturmaktadır. McGovern'ın değerlendirmesi, fiziksel, biyolojik ve kimyasal yöntemlerin konukçu dayanıklılığıyla birlikte ele alınması gerektiğini ortaya koymaktadır (McGovern, 2015). Enfeksiyon geliştikten sonra yalnızca yapraktan yapılan bir uygulamayla kök ve iletim dokusu kolonizasyonunun ortadan kaldırılması beklenmemelidir.
Fusarium solgunluğu, *F. oxysporum* f. sp. *radicis-lycopersici* kaynaklı kök ve kök boğazı çürüklüğünden ayrılmalıdır. İkinci hastalıkta kök korteksinde çürüme ve kök boğazında lezyonlar daha belirgindir; iç dokudaki renk değişimi çoğunlukla gövdenin alt bölümünde yoğunlaşır. Serin toprak koşullarının hastalığı desteklemesi de ayırıcı epidemiyolojik bir özelliktir. Bununla birlikte kesin ayrım, belirti gözlemine ek olarak laboratuvar incelemesi gerektirebilir (McGovern, 2015; UC IPM, 2013d).

Verticillium solgunluğu
Verticillium dahliae, domateste Verticillium solgunluğunun önemli etmenidir. Alt yapraklarda kenardan içeri doğru daralan V biçimli sararma ve nekroz alanları görülebilir. Bitkiler gelişme geriliği gösterir; gövdenin özellikle alt kesimindeki iletim dokusunda açık kahverengi renk değişimi oluşabilir. *Fusarium* solgunluğuyla belirti benzerliği bulunduğundan, yalnızca renk tonu veya solmanın tek taraflılığı kesin tanı için kullanılmamalıdır (UC IPM, 2013l).
Etmen mikrosklerotlarıyla toprakta kalabilmekte ve geniş konukçu dizisi nedeniyle kısa münavebe programlarından sınırlı ölçüde etkilenebilmektedir. Hastalık, *Fusarium* solgunluğuna göre daha serin koşullarda öne çıkma eğilimindedir. Uygun dayanıklılığa sahip çeşit ve anaç seçimi ile bulaşık toprağın taşınmasının engellenmesi önemlidir. Dayanıklılığın ırka bağlı olduğu dikkate alınmalı; bir çeşitteki dayanıklılık özelliği bütün yerel izolatlara genellenmemelidir. Hastalık bitkileri öldürmeden de gelişmeyi ve pazarlanabilir verimi azaltabildiğinden, değerlendirme yalnızca ölüm oranına dayandırılmamalıdır (UC IPM, 2013l, 2013k).

Phytophthora meyve çürüklüğü
İngilizce literatürde "buckeye rot" olarak adlandırılan hastalık, domates meyvelerinde *Phytophthora* türlerinin oluşturduğu çürüklüktür. *P. parasitica* ve *P. capsici* bu hastalıkla ilişkilendirilen etmenler arasındadır. Toprakla temas eden veya toprak sıçramasına maruz kalan meyvelerde açık ve koyu kahverengi konsantrik bantlar görülebilir. Aynı etmen grubu köklerde çürüklük ve buna bağlı gelişme geriliği ile solmaya da neden olabilir (UC IPM, 2013g).
Topraktaki serbest su, kötü drenaj ve aşırı sulama enfeksiyon için önemlidir. Yükseltilmiş yetiştirme yatakları, drenajın iyileştirilmesi, meyvelerin toprakla temasının azaltılması ve sulamanın düzenlenmesi temel mücadele önlemleridir. Kök bölgesi ile meyve enfeksiyonu birlikte izlenmelidir. Toprak su yönetimindeki sorunu çözmeden yalnızca meyveye yönelik koruma uygulamak, inokulumun

sürekliliğini ortadan kaldırmaz. Kimyasal uygulama gerektiğinde hedef etmenin oomycete olduğu dikkate alınmalı ve ürünün ilgili hastalık için ruhsatı doğrulanmalıdır (UC IPM, 2013g; T.C. Tarım ve Orman Bakanlığı, t.y.).

Tablo 1. Seçilmiş domates hastalıklarında ön tanıyı destekleyen özellikler

Hastalık	Ön tanıda öne çıkan özellik	İlk yönetim önceliği
Çökerten	Çıkış kaybı veya toprak seviyesinden devrilme	Fide ve yetiştirme ortamı hijyeni
Septoria yaprak lekesi	Küçük, açık merkezli ve piknitli lekeler	Su sıçraması ve yaprak ıslaklığı
Erken yanıklık	Yaşlı yapraklarda halkalı nekrotik lekeler	Artık yönetimi ve bitki gelişimi
Geç yanıklık	Hızla genişleyen lekeler, nemde beyaz sporulasyon	Erken saptama ve risk döneminde koruma
Antraknoz	Olgun meyvede dairesel, çökük lekeler	Zamanında hasat ve meyve hijyeni
Külleme	Beyaz koloniler veya sarı alanlarla sporulasyon	Düzenli gözlem ve erken müdahale
Güney yanıklığı	Kök boğazında beyaz misel ve küresel sklerotlar	Bulaşık alan ve kök boğazı yönetimi
Fusarium solgunluğu	Solma ve gövde boyunca damar kahverengileşmesi	Irka uygun dayanıklılık ve temiz fide
Verticillium solgunluğu	V biçimli sararma ve gelişme geriliği	Dayanıklılık ve toprak taşınmasının önlenmesi
Phytophthora meyve çürüklüğü	Toprağa yakın meyvede kahverengi halkalı bantlar	Drenaj ve meyve toprak temasının azaltılması

Tablo, ilgili hastalık bölümlerinde belirtilen kaynaklardan sentezlenmiştir. Belirtiler tek başına kesin tanı için yeterli değildir.

Entegre hastalık yönetimi

Tanı ve üretim alanının izlenmesi

Mücadele kararının ilk aşaması, belirtilerin dağılımı ve gelişme hızının üretim koşullarıyla birlikte değerlendirilmesidir. Yalnızca tek bir yaprağın görüntüsü; kök çürüklüğü, iletim demeti enfeksiyonu veya karışık enfeksiyonun ayırt edilmesi için yeterli değildir. İnceleme, yaprakların iki yüzünü, gövde kesitini, kök boğazını, kökleri ve meyveleri kapsamalıdır. Aynı bitkide birden fazla etmenin bulunabileceği göz önünde tutulmalıdır (Meadows ve ark., 2021; UC IPM, 2013e, 2013l).

İzolasyon yapılabilen etmenlerde kültürel ve morfolojik incelemeler moleküler verilerle desteklenebilir. *Alternaria* türlerinin ayrımında çok lokuslu yaklaşımın sağladığı çözünürlük, yalnızca belirti veya tek bir karaktere dayalı tanının sınırlarını göstermektedir (Woudenberg ve ark., 2014). Tanı sonucunun yönetim açısından değeri, "fungus bulundu" ifadesinden daha ileri gitmesine bağlıdır. Özellikle solgunluk etmenlerinde tür, konukçu özelleşmesi ve gerektiğinde ırk bilgisinin, çeşit veya anaç seçiminde kullanılabilir olması gerekir (Stokes ve ark., 2026).

Sağlıklı üretim materyali ve kültürel önlemler

Mücadele programı dikimden önce başlamalıdır. Üretim alanının hastalık geçmişi, önceki ürünler ve drenaj durumu incelenmeli; fide kaynağı ile çeşit seçimi bu bilgilere göre belirlenmelidir. Hastalıkla bulaşık materyalin taşınmasını engelleyen ekipman temizliği, fide hijyeni ve alanlar arasındaki iş akışının düzenlenmesi, sonraki uygulamaların başarısını desteklemektedir (UC IPM, 2013i).

Kültürel önlemler, enfeksiyon sürecinin hangi aşamasını hedeflediğine göre seçilmelidir. Malç ve bitki destekleme, topraktan yaprağa veya meyveye sıçramayı azaltabilir. Havalandırma, yaprakların kuruma süresini etkileyebilir. Drenaj ve sulama kontrolü ise oomycete kök ve meyve enfeksiyonlarında doğrudan önem taşır. Buna karşılık iyi havalandırılan bir serada toprak kökenli solgunluk etmeni ortadan kalkmış olmaz. Önlemlerin etkisi, hedef etmenin biyolojisiyle açıklanmalıdır (Meadows ve ark., 2021; UC IPM, 2013h, 2013g).

Dayanıklı çeşitler ve aşılı fide

Dayanıklı çeşit veya anaç kullanımı, özellikle toprak kökenli hastalıklarda öncelikli seçeneklerden biridir. Bununla birlikte dayanıklılık değerlendirmesi; etmen, ırk, anaç ve kalem kombinasyonu ile üretim ortamını kapsamalıdır. Tohum veya fide etiketindeki dayanıklılık kodlarının ilgili etmenle eşleştirilmesi gerekir. Bir hastalığa dayanıklı anaç seçimi, diğer kök hastalıklarına karşı koruma sağlandığını göstermez (Stokes ve ark., 2026; UC IPM, 2013k).

El-Komy ve ark. (2026), solarizasyon, *Trichoderma asperellum* suş karışımı ve dayanıklı anaca aşılama uygulamalarını domates *Fusarium* solgunluğuna karşı tek başına ve kombinasyonlar halinde değerlendirmiştir. Üçlü uygulama, çalışmanın sera ve tarla koşullarında hastalığı baskılama bakımından öne çıkmıştır. Bu sonuç, farklı mekanizmaları birleştirmenin yararlı olabileceğine ilişkin deneysel kanıt sunmaktadır. Ancak kullanılan anaç, antagonist karışımı ve uygulama koşulları değiştirilerek aynı etkinliğin elde edileceği varsayılmamalıdır.

Tohum ve yetiştirme ortamı uygulamaları

Tohum koruma uygulamalarının temel hedefi, çimlenme ve erken fide döneminde enfeksiyon riskini azaltmaktır. Uygulamanın başarısı, hedef patojenin doğru belirlenmesine bağlıdır. Tek bir ürünün hem *Rhizoctonia* hem bütün oomycete etmenlere aynı ölçüde etkili olduğu kabul edilmemelidir. Uygun yetiştirme ortamı, kontrollü sulama ve hijyen, tohum uygulamasının tamamlayıcılarıdır (UC IPM, 2013b; FRAC, 2026).

Toprak veya substratın fiziksel yöntemlerle işlenmesi, başlangıç inokulumunu azaltmaya yöneliktir. Buhar uygulaması, özellikle kontrollü yetiştirme ortamlarında değerlendirilebilir. Solarizasyonun etkinliği ise toprakta oluşan sıcaklık ve uygulama koşullarıyla ilişkilidir. Bu yöntemler toprağın daha sonra yeniden bulaşmasını önlemez. Bu nedenle işlem sonrasında temiz fide, ekipman ve yetiştirme materyali kullanımı sürdürülmelidir. Fiziksel uygulamaların biyolojik mücadele ve dayanıklılıkla birleştirilmesi, tek yönteme bağımlılığı azaltabilecek bir seçenektir (McGovern, 2015; UC IPM, 2013d; El-Komy ve ark., 2026).

Biyolojik mücadele ve kanıtların yorumlanması

Domates hastalıklarına karşı biyolojik mücadelede *Trichoderma* ve *Bacillus* cinslerine ait suşlar önemli araştırma konularıdır. Antagonistik etkinlik; patojene doğrudan etki, kök çevresinde yerleşme ve bitkinin savunma yanıtlarının değişmesi gibi süreçlerle ilişkili olabilir. Ancak bir mikroorganizmanın tür adı, biyolojik etkinliğini tek başına açıklamaz. Suşun özellikleri, formülasyon, canlılık, uygulama yeri ve zamanlaması birlikte değerlendirilmelidir (Bandara ve Kang, 2024; Zhang ve ark., 2025; Xu ve ark., 2026).

Bandara ve Kang (2024), *T. virens* uygulama zamanının domates gelişimi ve rizosferin baskılayıcı özellikleri üzerindeki etkisini araştırmıştır. Dikim sırasında yapılan uygulama, incelenen koşullarda bitki gelişimi ve bazı baskılayıcılık ölçütleri bakımından öne çıkmıştır. Bununla birlikte çalışmada kullanılan rizosfer metabolitleri ve uçucu bileşik deneyleri, ticari tarlada gerçekleşecek hastalık kontrolüyle aynı ölçüt değildir. Bu ayrım, mekanizmayı destekleyen sonuçların doğrudan geniş ölçekli üretim önerisine dönüştürülmemesi gerektiğini göstermektedir.

Zhang ve ark. (2025), *Rhizophagus irregularis* ve *T. harzianum* uygulamalarının domates köklerinde *F. oxysporum* kolonizasyonunu azalttığını ve savunma hormonlarıyla ilişkili değişiklikler oluşturduğunu bildirmiştir. Ancak birlikte uygulama, tekli uygulamalara göre ilave baskılama sağlamamıştır. Bu bulgu, "daha fazla yararlı mikroorganizma daha yüksek koruma sağlar" varsayımının her kombinasyon için geçerli olmadığını ortaya koymaktadır. Mikrobiyal karışımların uyumluluğu ve katkısı deneysel olarak sınanmalıdır.

Xu ve ark. (2026) tarafından yürütülen çalışmada *B. velezensis* BV25, hem doğrudan antagonistik özellikler hem de sera koşullarında *Fusarium* solgunluğunu baskılayıcı etki göstermiştir. Savunmayla ilişkili enzim aktiviteleri ve genomik bulgular, olası mekanizmaları desteklemiştir. Bununla birlikte bir biyosentetik gen kümesinin saptanması, ilgili metabolitin her üretim koşulunda aynı düzeyde oluştuğunu kanıtlamaz. Laboratuvar inhibisyonu, sera hastalık şiddeti ve tarla verimi birbirinden farklı sonuç değişkenleridir.

Bu çalışmalar birlikte değerlendirildiğinde, biyolojik mücadele adaylarının seçimi için hastalık baskılama yanında kök bölgesinde kalıcılık, bitki gelişimi, uygulama maliyeti ve diğer üretim girdileriyle uyumluluğun da izlenmesi gerektiği sonucuna ulaşılmaktadır. *Fusarium*'a karşı alınan olumlu sonuçlar, *Septoria*, külleme veya geç yanıklığa doğrudan genellenmemelidir. Her hedef hastalık için uygulama yeri ve etkinliğin yeniden değerlendirilmesi gerekir.

Fungisitlerin rasyonel kullanımı

Fungisit seçimi, doğru tanıyı izlemelidir. FRAC sınıflandırması aktif maddeleri etki mekanizması ve direnç ilişkileri bakımından gruplandırmaktadır. Farklı ticari adlarla satılan ürünler aynı grupta yer alabileceğinden, yalnızca marka değişimi yeterli değildir. Programda ardışık uygulamalar, izin verilen uygulama sayısı ve karışım bileşenleri birlikte değerlendirilmelidir. Bütün hastalıklar için tek bir sabit ilaçlama aralığı önermek yerine, ürün etiketi ve hastalık riski esas alınmalıdır (FRAC, 2026).

Türkiye'de ürün seçimi yapılırken domates, hedef hastalık, yetiştirme biçimi ve uygulama yöntemi için güncel ruhsat ve etiket bilgileri Tarım ve Orman Bakanlığı Bitki Koruma Ürünleri Veri Tabanı üzerinden doğrulanmalıdır (T.C. Tarım ve Orman Bakanlığı, t.y.). Yabancı yayım kaynaklarındaki dozlar ve hasat öncesi bekleme süreleri Türkiye'ye doğrudan aktarılamaz. Derleme kapsamında belirli bir ticari ürün reçetesi yerine, uygulamanın hedefi ve direnç yönetimi ilkeleri değerlendirilmiştir.

Agronomik ve ekonomik değerlendirme

Bir mücadele yönteminin başarısı, yalnızca hastalık şiddetindeki azalma üzerinden belirlenmemelidir. Fide dönemindeki kayıplar yeniden dikim gereksinimi oluştururken, yaprak hastalıkları üretim süresini ve meyve kalitesini etkileyebilir. Meyve çürüklükleri doğrudan ayıklama kaybı yaratır. Solgunluk hastalıkları ise bitki canlılığını azaltarak hasat boyunca biriken kayıplara neden olabilir (UC IPM, 2013b, 2013a, 2013e, 2013l).

Üretim sistemi açısından karşılaştırma yapılırken pazarlanabilir verim, kalite sınıfları, fide veya anaç maliyeti, işçilik ve uygulama giderleri birlikte kaydedilmelidir. Hastalık baskısının düşük olduğu bir sezonda pahalı bir uygulamanın ekonomik getirisi sınırlı kalabilir; yüksek baskı altında ise aynı uygulama üretimin devamlılığını sağlayabilir. Bu nedenle farklı yıllar ve lokasyonlardan elde edilen veriler, tek sezonluk sonuçlara göre daha güçlü bir değerlendirme zemini oluşturur.

Sentezlenen bilgiler, ortak kültürel önlemlerin birden fazla hastalık için yarar sağlayabileceğini göstermektedir. Bununla birlikte her önlemin bütün etmenlerde eşdeğer etkisi bulunmamaktadır. Ekonomik karşılaştırmada, önlenen kayıpla uygulama maliyeti arasındaki ilişki kadar, yöntemin üretici tarafından düzenli uygulanabilirliği de dikkate alınmalıdır. Bu değerlendirme özellikle küçük işletmelerde ekipman, sağlıklı fideye erişim ve teknik bilgi gibi sınırlamalarla birlikte yapılmalıdır.

SONUÇ

Domateste fungal ve oomycete hastalıklarının sürdürülebilir yönetimi, başlangıç inokulumunun azaltılması ve enfeksiyon koşullarının sınırlandırılmasıyla başlamaktadır. Doğru tanı, hastalıksız fide ve yetiştirme materyali, etmen ve ırka uygun dayanıklılık, su yönetimi ve sanitasyon programın temel bileşenleridir. Biyolojik ve kimyasal uygulamalar, bu temeli güçlendirecek biçimde seçilmelidir.

Güncel çalışmalar, biyolojik mücadelede suş ve zamanlama etkilerinin önemli olduğunu; fiziksel uygulamalar, aşılama ve antagonistlerin bazı koşullarda birlikte yarar sağlayabildiğini göstermektedir. Buna karşılık her kombinasyon ek yarar üretmemektedir. Türkiye'de farklı yetiştirme sistemlerini temsil eden çok yıllı denemeler, yerel etmen ve ırk dağılımının belirlenmesi, fungisit duyarlılığının izlenmesi ve biyolojik ürünlerin pazarlanabilir verim üzerinden değerlendirilmesi öncelikli araştırma alanlarıdır. Üreticiye aktarılacak programlar, bu verilerle desteklenen ve uygulama sonucuna göre güncellenen programlar olmalıdır.

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BIOCONTROL POTENTIAL OF SOME TRICHODERMA SPP. AGAINST *SOME FUSARIUM SPP. AND MONILIA LAXA*

BAZI TRICHODERMA TÜRLERİNİN FUSARIUM SPP. VE MONILIA LAXA'YA KARŞI BİYOLOJİK MÜCADELE POTANSİYELİ

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Abstract
Agricultural production faces increasingly significant challenges. Diseases caused by fungal pathogens lead to substantial economic losses worldwide by reducing crop yield and quality. Although conventional synthetic pesticides have long been widely used to control these pathogens, their continuous and intensive use has contributed to persistent problems, including environmental pollution, disruption of ecological balance, food safety risks, and pesticide residues. These adverse effects highlight the need to develop sustainable, environmentally friendly alternatives for disease management in agricultural production. Among approaches aimed at reducing reliance on chemical inputs, biological control using biocontrol agents stands out as a promising strategy for environmentally sustainable agriculture, owing to its potential to effectively suppress target pathogens.
In the present study, the biocontrol efficacy of selected *Trichoderma* spp., including *T. asperellum*, *T. harzianum*, *T. harnatum*, and a commercial *T. harzianum*-based product, obtained from different hosts and sources, was evaluated against *Fusarium avenaceum*, *F. citricola*, *F. acuminatum*, and *Monilinia laxa*. The antagonistic activity of the tested *Trichoderma* isolates was investigated against *Fusarium* species associated with disease development and yield losses in woody plants, as well as against *M. laxa*, an important fungal pathogen responsible for severe fruit rot, particularly in stone fruits. The antagonistic potential of the isolates was assessed under in vitro conditions using dual-culture and double-plate assays. In the dual-culture assays, the effects of the *Trichoderma* isolates on the radial mycelial growth of the target pathogens were evaluated, and their ability to inhibit pathogen growth was determined. Double-plate assays were additionally performed to investigate the potential contribution of volatile or diffusible antifungal compounds to the antagonistic interactions.
The results demonstrated that *T. harzianum* isolated from the nut rhizosphere exhibited strong antagonistic activity, significantly inhibiting the mycelial growth of *F. acuminatum*. Furthermore, the *T. asperellum* isolate obtained from the apple rhizosphere and the commercial *T. harzianum*-based product showed high efficacy against *Monilinia laxa*, indicating their potential as promising biological control agents against this important fruit pathogen.
Keywords: Antogonistic activity, in vitro, mycoparasitic fungus

Özet
Tarımsal üretimde fungal patojenlerin neden olduğu hastalıklar, ürün verimi ve kalitesinde küresel ölçekte ciddi ekonomik kayıplara yol açmaktadır. Bu patojenlerle mücadelede uzun yıllardır konvansiyonel sentetik pestisitler yaygın olarak kullanılsa da, bu kimyasalların sürekli ve yoğun kullanımı çevre kirliliği, ekolojik dengenin bozulması, gıda güvenliği riskleri ve kalıntı problemleri gibi kronik sorunları beraberinde getirmiştir. Bu olumsuzluklar, tarımsal üretimde sürdürülebilir, çevre dostu ve alternatif hastalık yönetim stratejilerinin geliştirilmesini zorunlu kılmaktadır. Kimyasal girdilere olan bağımlılığı azaltmayı hedefleyen yaklaşımlar arasında, biyo-ajanların kullanımıyla şekillenen biyolojik

mücadele, hedef patojenleri etkili bir şekilde baskılama potansiyeliyle çevre dostu tarım modellemelerinde güçlü bir alternatif olarak öne çıkmaktadır. Bu çalışmada, farklı konukçu ve kaynaklardan elde edilen *Trichoderma* spp. izolatlarının; *T. asperellum, T. harzianum, T. harnatum* ve ticari *T. harzianum* esaslı bir ürünün, *Fusarium avenaceum, F. citricola, F. acuminatum* ve *Monilinia laxa*'ya karşı biyolojik mücadele etkinliğinin belirlenmesi amaçlanmıştır. Test edilen *Trichoderma* izolatlarının, odunsu bitkilerde hastalık gelişimi ve verim kayıplarıyla ilişkili *Fusarium* türleri ile özellikle sert çekirdekli meyvelerde önemli bir hastalık etmeni olan ve ciddi meyve çürüklüklerine neden olan *M. laxa* üzerindeki antagonistik aktiviteleri in vitro koşullarda değerlendirilmiştir. İzolatların antagonistik potansiyeli, ikili kültür ve çift petri (double-plate) testleri kullanılarak belirlenmiştir. İkili kültür testlerinde, *Trichoderma* izolatlarının test edilen patojenlerin radyal misel gelişimi üzerindeki etkileri değerlendirilmiş ve patojen gelişimini engelleme düzeyleri belirlenmiştir. Ayrıca, antagonistik etkileşimlerde uçucu veya difüze olabilen antifungal bileşiklerin olası katkısını araştırmak amacıyla çift petri testleri gerçekleştirilmiştir.
Elde edilen sonuçlar, ceviz rizosferinden izole edilen *T. harzianum* izolatının güçlü antagonistik aktivite gösterdiğini ve *F. acuminatum*'un misel gelişimini önemli ölçüde engellediğini ortaya koymuştur. Ayrıca, elma rizosferinden elde edilen *T. asperellum* izolatı ile ticari *T. harzianum* esaslı ürünün *Monilinia laxa*'ya karşı yüksek etkinlik gösterdiği ve bu nedenle söz konusu önemli meyve patojenine karşı umut vadeden biyolojik mücadele ajanları olabileceği belirlenmiştir.
Anahtar kelimeler: Antagonistik aktivite, in vitro, mikoparazitik fungus

INTRODUCTION

The genus *Fusarium* comprises a diverse group of filamentous ascomycetous fungi that are widely distributed in agricultural and natural ecosystems and includes numerous economically important plant pathogens. Members of the genus are associated with a broad range of diseases affecting cereals, legumes, vegetables, fruit crops, ornamentals, and forest plants, causing root rot, crown rot, stem and fruit diseases, vascular wilts, and seedling diseases. The importance of *Fusarium* extends beyond direct crop losses because several species are also capable of producing mycotoxins that pose significant risks to food and feed safety (Dean et al., 2012; Ma et al., 2013; Munkvold et al., 2021).
Stone fruit production is significantly affected by *Monilinia laxa*, a destructive fungal pathogen associated with brown rot, blossom blight, and spur infections (Uysal, 2024).

MATERIALS AND METHODS

In this study, two phytopathogenic Fusarium isolates (*F. citricola*, *F. acuminatum*) and *T. asperellum, T. harzianum, T. harnatum* strain as biocontrol agents which had been previously characterised with molecular techniques were used in in vitro assays. The pathogens and antagonistic fungi were grown at 26 ± 1ºC for 7 days on potato dextrose agar (PDA). The fungal discs with a 5 mm diameter of 7-day-old fresh cultures were used in all experiments.

Dual Culture Assay

Dual culture tests were conducted according to the method proposed by (Rahman et al, 2009). Briefly, mycelium discs (5 mm) of *Fusarium* spp. and *Trichoderma* isolates were taken from the margins of 7-day-old cultures and placed at a distance of 3 cm in a PDA medium. Plates prepared by inoculating only pathogens were considered as a control group. All groups were incubated at 26 ± 1 ºC for 7 days.

Isolation of Fungi

For the isolation of the target fungal pathogens, symptomatic plant tissues showing root, crown, stem, or fruit rot were collected from the respective hosts. Samples were thoroughly washed under running tap water and blotted dry with sterile paper towels. Small tissue pieces were excised from the margins between healthy and necrotic tissues and surface-disinfested by immersing them in 0.1% sodium hypochlorite (NaOCl) for 1–3 min, depending on tissue tenderness. The disinfected tissues were rinsed with sterile distilled water and blotted dry. Small pieces approximately 2–3 mm in size were then aseptically transferred onto appropriate isolation media and incubated under suitable conditions. Emerging fungal colonies were subcultured onto fresh media and purified for subsequent morphological and molecular identification (Agrios, 2005).
Trichoderma isolates were obtained from the rhizosphere soil of the respective host plants, including apricot, hazelnut, apple, and strawberry. Rhizosphere soil samples were collected from the root zone of

the plants and processed for the isolation of *Trichoderma* spp. The recovered isolates were purified and maintained on appropriate culture media for subsequent morphological identification and antagonistic assays against the target fungal pathogens. The isolation of *Trichoderma* from rhizosphere soil was performed following commonly used procedures for the recovery of *Trichoderma* spp. from soil and plant-associated environments (Elad et al., 1981; Papavizas, 1985).

Molecular Identificatıon of The Fungi Used

Dna Extraction

The isolates were grown on potato dextrose agar (PDA) at 24°C for 10–12 days. Genomic DNA was extracted using the Qiagen DNeasy Blood & Tissue Kit (Qiagen, Madison, WI, USA) according to the manufacturer's protocol.

The internal transcribed spacer (ITS) region was amplified using the ITS1 and ITS4 primer pair for *Trichoderma* spp. and *Monilinia laxa* (White et al., 1990, Kroon et al. 2004). PCR amplification was performed with an initial denaturation at 94°C for 4 min, followed by 35 cycles of denaturation at 94°C for 60 s, annealing at 58°C for 60 s, and extension at 72°C for 60 s, followed by a final extension at 72°C for 5 min., The RPB2 region was amplified using the primer pair fRPB2-5F/fRPB2-7cR for *Fusarium* spp. (Liu et al., 1999). PCR amplification was performed with an initial denaturation at 95°C for 5 min, followed by 35 cycles of denaturation at 95°C for 1 min, annealing at 48°C for 2 min, a temperature increase of 0.2°C s^{-1} to 72°C, and extension at 72°C for 2 min, followed by a final extension at 72°C for 10 min (Table 1). PCR reactions were performed in a final volume of 50 µL, consisting of 5 µL of DNA template (approximately 10 ng), 26 µL of Thermo Scientific™ PCR Master Mix, 15 µL of nuclease-free water (Merck), and 2 µL of primers.

Table 1. Primers used for PCR amplification and molecular identification of the fungal isolates.

Target gene region	Primer sequences	PCR protocol	Product length (bp)	References
ITS	ITS1: 5'TCCGTAGGTGAACCTGCGG3' ITS4: 5'TCCTCCGCTTATTGATATGC3'	94 °C-4 m 94 °C-60 s 58 °C-60 s 72 °C-60 s **35 cycle** 72 °C-5 m	590 bp	White et al. 1990; Kroon et al. 2004
RPB2	fRPB2-5F:GAYGAYMGWGATCAYTTYGG fRPB2-7cR: CCCATRGCTTGYTTRCCCAT	95 °C 5 m, 95 °C 1 m 48 °C 2 dk 72 °C 2 m **35 cycle** 72 °C 10 m	989 bp	Liu et al. 1999

Agarose Gel Electrophoresis and PCR Product Selection

The PCR products were separated by electrophoresis on a 1.5% agarose gel prepared in 1× TAE buffer (40 mM Tris-acetate, 1 mM EDTA, pH 8.0). To prepare the agarose gel, 1.5 g of agarose was added to 100 mL of 1× TAE buffer in an Erlenmeyer flask and heated in a microwave oven until completely dissolved. After the solution had cooled to a suitable temperature, 5 µL of Nucleic Acid Gel Staining Solution (per 100 mL of gel) was added and thoroughly mixed. The molten agarose was then poured into a horizontal electrophoresis chamber fitted with an appropriate comb and allowed to solidify.

Following electrophoresis, the gel was visualized using a UV transilluminator imaging system. Isolates producing positive bands of the expected size corresponding to the target gene regions were identified, and the respective PCR products were submitted for sequencing.

The internal transcribed spacer (ITS) regions of ITS-4 and ITS-5, all *Trichoderma* spp and *Fusarium* spp. the all isolates were amplified and the obtained gene sequences were compared with the ones deposited in GenBank. All the fungi with the sequences deposited in GenBank.

Statistical analysis

The antagonistic activity of the *Trichoderma* isolates against the pathogen was evaluated using the dual-culture technique. The percentage inhibition of radial mycelial growth (PIRG) was calculated according to Skidmore and Dickinson (1976) using the following formula: PIRG (%) = [(C − T) / C] × 100, where C represents the radial growth of the pathogen in the control treatment and T represents the radial growth of the pathogen in the presence of the *Trichoderma* isolate. Each treatment was evaluated using two experimental replicates, and the mean radial growth and percentage inhibition values were calculated. Because only two replicates were available for each treatment, the results were evaluated using descriptive statistics, and no inferential statistical tests were performed.

Results and Discussion

Molecular identification of the fungal isolates

Molecular identification was performed using ITS sequences for the Trichoderma isolates and *Monilinia laxa*, whereas the RPB2 region was used for the identification of the Fusarium isolates. PCR amplification produced products of the expected sizes for the target regions, and positive amplification products were selected for sequencing. The obtained sequences were compared with sequences deposited in GenBank to support the identification of the fungal isolates.

The antagonistic activities of the tested Trichoderma isolates against the target Fusarium species were evaluated using the dual-culture assay. Differences were observed among the Trichoderma isolates in their ability to suppress the radial mycelial growth of the tested pathogens. The percentage inhibition of radial mycelial growth (PIRG) was calculated based on the radial growth of the pathogens in the control plates and in the presence of Trichoderma isolates.

The antagonistic activity of the tested *Trichoderma* isolates against *Fusarium acuminatum* varied among the isolates. The pathogen showed a mean radial growth of 53.0 mm in the control treatment, whereas the presence of *Trichoderma* isolates reduced pathogen growth to 23.0–30.0 mm. The highest inhibition rate was observed for T-5 (*Trichoderma harnatum*) isolated from strawberry, with 56.6% inhibition and a mean pathogen growth of 23.0 mm. This was followed by T-2 (*T. harzianum*) isolated from walnut, with 54.7% inhibition, and T-3 (*Trichoderma asperellum*) isolated from apple, with 51.9% inhibition. The T-4 *T. harzianum* isolate and T-1 *T. harzianum* isolate obtained from apricot showed 45.3% and 43.4% inhibition, respectively (Table 2) (Figure1). These results indicate that all tested *Trichoderma* isolates suppressed the mycelial growth of *F. acuminatum* compared with the pathogen control, with T-5 showing the highest observed antagonistic activity. The inhibitory effect may be associated with competition for nutrients and space, mycoparasitism, and the production of antifungal metabolites, which are among the mechanisms commonly reported for *Trichoderma* spp. (Elad et al., 1981; Papavizas, 1985).

Table 2. Antagonistic activity of Trichoderma isolates against Fusarium acuminatum based on dual-culture assay.

Isolate no	Isolate source	Pathogen fungal growth (mm)	Trichoderma growth (mm)	Inhibition of radial growth (%)	Growth differences (T - P) (mm)
T-1	Apricot- *T. harzianum*	30,00	63,50	**43,4%**	33,50
T-2	Walnut-*T. harzianum*	24,00	58,00	**54,7%**	34,00
T-3	Apple- *Trichoderma asperellum*	25,50	66,00	**51,9%**	40,50
T-4	*Trichoderma harzianum*	29,00	60,00	**45,3%**	31,00
T-5	Strawberry- *T. harnatum*	23,00	61,00	**56,6%**	38,00
Control	*Fusarium acuminatum*	53,00	0,00	**0,0%**	-

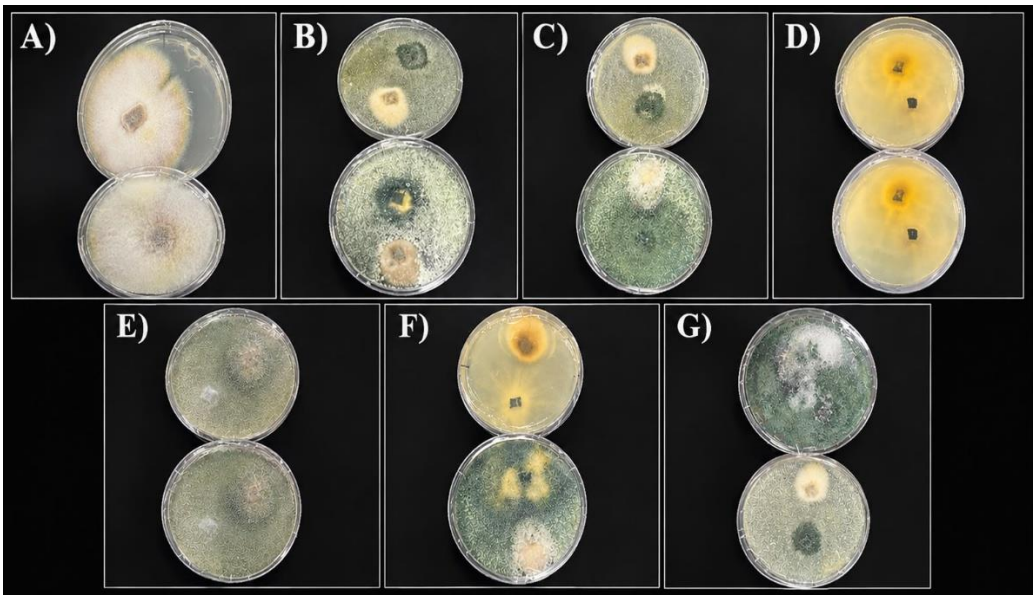


Figure 1. Dual-culture assays of different *Trichoderma* isolates against *Fusarium acuminatum*: A) *Fusarium acuminatum* control, B) *Trichoderma harzianum* isolate isolated from Walnut, C) *T. harzianum* commercial fertilizer product, D) *Trichoderma asperellum* isolated from apple , E) *Trichoderma harzianum* isolated from Strawberry , F) *Trichoderma harzianum* isolated from, G) Trichoderma harzianum Apricot

The growth of *Fusarium citricola* was markedly reduced in the presence of all tested *Trichoderma* isolates. Compared with 46.0 mm growth in the control, pathogen growth ranged from 12.5 to 18.0 mm in the dual-culture treatments. The greatest suppression was obtained with T-3 (*Trichoderma asperellum*) from apple and T-4 (*T. harzianum*), both providing 72.8% inhibition. T-2 (*T. harzianum*) from walnut also showed strong activity (70.7%), while T-5 (*Trichoderma harnatum*) and T-1 (*T. harzianum*) resulted in 62.0% and 60.9% inhibition, respectively (Table 3) (Figure2). The marked reduction in pathogen growth suggests a strong antagonistic interaction between the tested *Trichoderma* isolates and *F. citricola*. This activity may involve rapid colonization, competition, and antifungal metabolite production. As the experiment was based on two replicates, the findings are considered preliminary and should be validated in further studies.

Table 3. Antagonistic activity of Trichoderma isolates against Fusarium citricola based on dual-culture assay.

Isolate no	**Isolate source**	**Pathogen fungal growth (mm)**	**Trichoderma growth (mm)**	**Inhibition of radial growth (%)**	**Growth differences (T - P) (mm)**
T-1	Apricot- *T. harzianum*	18,00	71,50	**60,9%**	53,50
T-2	Walnut-*T. harzianum*	13,50	72,50	**70,7%**	59,00
T-3	Apple- *Trichoderma asperellum*	12,50	71,50	**72,8%**	59,00
T-4	*Trichoderma harzianum*	12,50	74,00	**72,8%**	61,50
T-5	Strawberry- *T. harnatum*	17,50	71,00	**62,0%**	53,50
Control	*Fusarium citricola*	46,00	0,00	**0,0%**	-

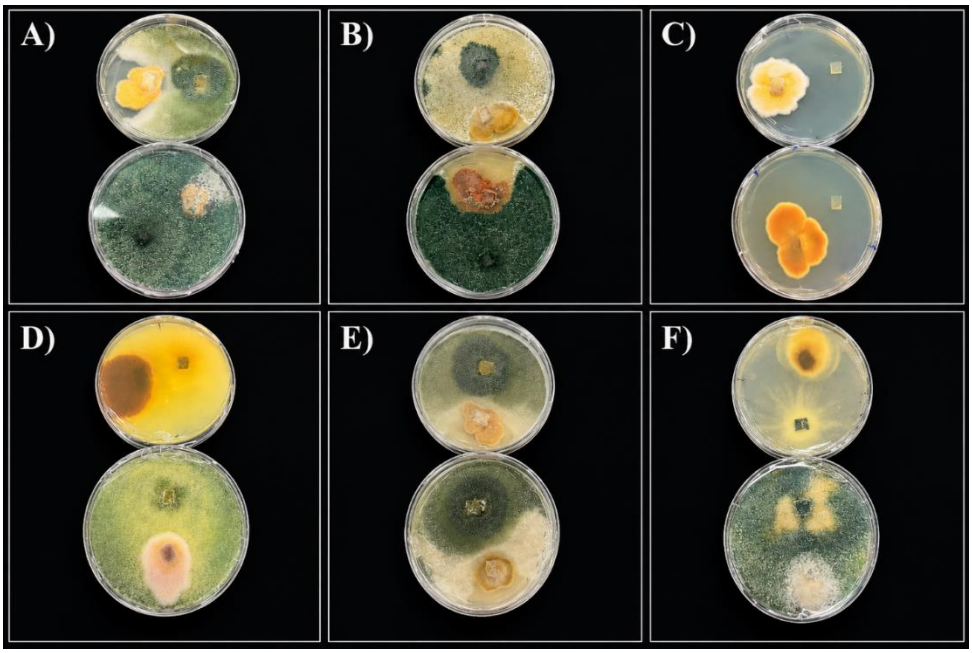


Figure 2. Dual-culture assays of different *Trichoderma* isolates against *Fusarium citricola*: A) *T. harzianum* commercial fertilizer product, B) *Trichoderma harzianum* isolate isolated from Walnut, C) *Fusarium citricola* control, D) *T. harzianum* commercial fertilizer product, E) *Trichoderma harzianum* isolated from Strawberry- T. F) *Trichoderma asperellum* isolated from Apple, G) *Trichoderma harzianum* commercial fertilizer product

The antagonistic activity of the tested *Trichoderma* isolates against *Monilinia laxa* varied among the treatments. The mean radial growth of *M. laxa* was 46.0 mm in the pathogen control, whereas the presence of *Trichoderma* isolates reduced pathogen growth to 12.5–18.0 mm. The highest inhibition was observed with the *Trichoderma asperellum* isolate obtained from the apple rhizosphere (T-3) and the commercial *T. harzianum*-based product (T-4), both showing a mean pathogen growth of 12.5 mm and 72.83% inhibition. These treatments were followed by the hazelnut-rhizosphere isolate (T-2) with 70.65% inhibition, while the strawberry (T-5) and apricot (T-1) isolates showed 61.96% and 60.87% inhibition, respectively (Table 4) (Figure 3). The strong inhibitory activity observed in T-3 and T-4 indicates their potential as biological control agents against *M. laxa*. The observed antagonism may be associated with competition for nutrients and space, mycoparasitism, and the production of antifungal metabolites, mechanisms commonly reported for *Trichoderma* spp. (Elad et al., 1981; Papavizas, 1985).

Table 4. Antagonistic activity of Trichoderma isolates against Monilia laxa based on dual-culture assay.

Isolate no	Isolate source	Pathogen fungal growth (mm)	Trichoderma growth (mm)	Inhibition of radial growth (%)	Growth differences (T - P) (mm)
T-1	Apricot- *T. harzianum*	18,00	71,50	**60,9%**	53,50
T-2	Walnut- *T. harzianum*	13,50	72,50	**70,7%**	59,00
T-3	Apple- *Trichoderma asperellum*	12,50	71,50	**72,8%**	59,00
T-4	*Trichoderma harzianum*	12,50	74,00	**72,8%**	61,50
T-5	Strawberry- *T. harnatum*	17,50	71,00	**62,0%**	53,50
Control	*Monilia laxa*	46,00	0,00	**0,0%**	-

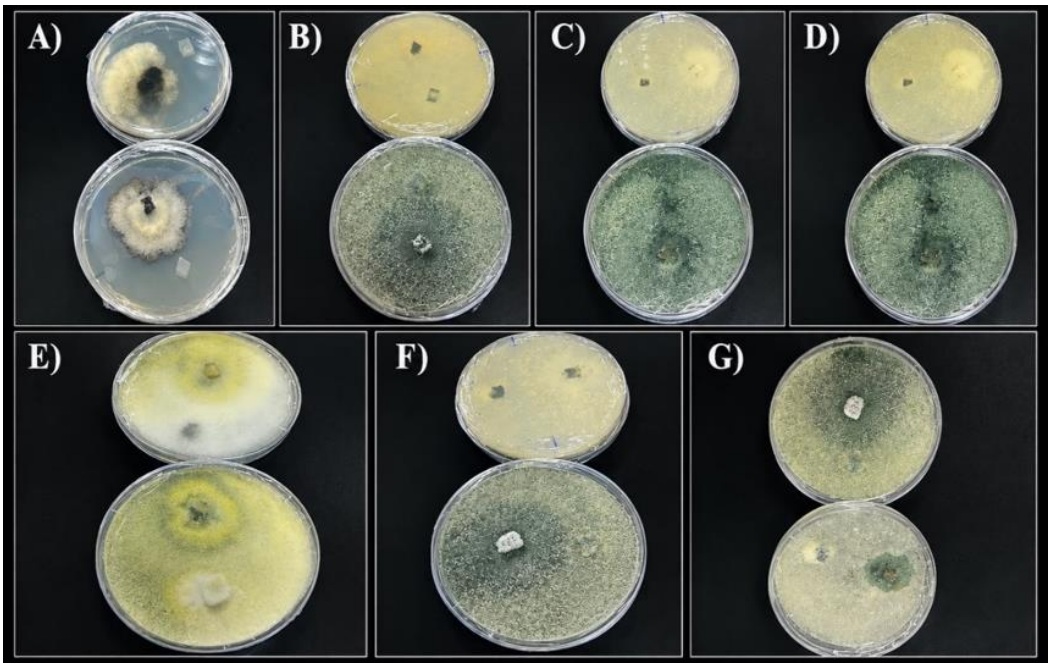


Figure 3. Dual-culture assays of different *Trichoderma* isolates against *Monilia laxa* A) *Monilia laxa* control, B) *Trichoderma harzianum* isolate isolated from Walnut, C) *T. harzianum* commercial fertilizer product, D) *Trichoderma asperellum* isolate isolated from apple, E) *Trichoderma harzianum* isolated from Apricot , F) *Trichoderma harzianum* isolate , G) *Trichoderma harzianum* isolate isolated from Strawberry

The antagonistic potential of *Trichoderma* spp. against *Fusarium* species has been widely demonstrated in previous studies. Several reports have shown that *T. harzianum*, *T. asperellum*, and other *Trichoderma* species can effectively restrict the mycelial growth of different *Fusarium* pathogens in dual-culture assays. For example, *T. harzianum* has been reported to inhibit *Fusarium oxysporum* through competition for nutrients and space, as well as mycoparasitic interactions, while *T. asperellum* has also shown considerable antagonistic activity against different *Fusarium* species (Bunbury-Blanchette and Walker, 2019; Modrzewska et al., 2022).

In addition to *Fusarium*, biological control approaches have also been investigated against *Monilinia laxa*, an important pathogen of stone fruits. Previous in vitro studies have demonstrated that microbial antagonists can substantially suppress the mycelial growth of *M. laxa*, highlighting the potential of biological control as an alternative or complementary approach to conventional disease management.

Conclusion

Overall, the results indicate that the tested Trichoderma isolates differed in their antagonistic activity against the target pathogens. The walnut-rhizosphere *T. harzianum* isolate showed strong activity against *F. acuminatum*, whereas the apple-rhizosphere *T. asperellum* isolate and the commercial *T. harzianum*-based product showed high inhibitory activity against *M. laxa*. These findings demonstrate that selected Trichoderma isolates may have potential as biological control agents against important fungal pathogens of woody and fruit crops.

However, the present study was conducted under in vitro conditions and therefore the observed antagonistic activity cannot be directly extrapolated to disease suppression under greenhouse or field conditions. Environmental factors, host–microbe interactions, pathogen population structure, formulation stability, and application timing may substantially influence biocontrol efficacy under natural conditions.

Taken together, the findings provide preliminary evidence for the biocontrol potential of selected *Trichoderma* isolates and indicate that strain selection is a critical factor in the development of effective biological control strategies against *Fusarium* spp. and *Monilinia laxa*.

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DETERMINATION OF IN VITRO BIOCONTROL EFFICACY OF SOME TRICHODERMA SPP. AGAINST FUSARIUM OXYSPORUM

BAZI TRICHODERMA TÜRLERİNİN FUSARIUM OXYSPORUM'A KARŞI İN-VİTRO KOŞULLARDA BİYOLOJİK MÜCADELE ETKİNLİĞİNİN BELİRLENMESİ

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Abstract
Phytopathogenic fungi are among the major constraints affecting agricultural production, causing considerable yield and quality losses in a wide range of crops. The management of fungal diseases has traditionally relied heavily on synthetic fungicides and other chemical pesticides. However, the intensive and continuous use of these chemicals has raised increasing concerns regarding environmental contamination, adverse effects on non-target organisms, pesticide residues in food, and the development of resistant pathogen populations. Therefore, the development of environmentally friendly and sustainable disease management strategies that can reduce dependence on synthetic agrochemicals has become increasingly important. In this context, biological control using beneficial microorganisms represents a promising alternative approach for the sustainable management of plant diseases. The present study aimed to evaluate the in vitro biocontrol potential of different *Trichoderma* spp. isolates against *Fusarium oxysporum*, a phytopathogenic fungus associated with disease development and yield losses in woody plants. The *Trichoderma* isolates evaluated in this study included *T. asperellum* obtained from the apple rhizosphere, as well as *Trichoderma harzianum* isolates obtained from strawberry, walnut, and apricot hosts and a commercial *T. harzianum*-based fertilizer product. The antagonistic activity of the isolates against *F. oxysporum* was investigated using dual culture assays and double-plate assays under in vitro conditions. In the dual culture tests, the effects of the *Trichoderma* isolates on the radial mycelial growth of *F. oxysporum* were evaluated, and the percentage inhibition of mycelial growth was determined. Double-plate assays were additionally performed to assess the potential role of volatile or diffusible antifungal metabolites in the antagonistic interactions. The results demonstrated that the *T. asperellum* isolate obtained from the apple rhizosphere exhibited a significant inhibitory effect on the mycelial growth of *F. oxysporum* in the dual culture assay. This finding indicates that the isolate has considerable antagonistic potential and may be a promising candidate for further evaluation as a biological control agent. In contrast, no statistically significant differences were detected among the treatments in the control assays. Overall, the findings suggest that selected *Trichoderma* isolates, particularly *T. asperellum* from the apple rhizosphere, may have potential for the biological suppression of *F. oxysporum* and could contribute to the development of sustainable alternatives to conventional chemical disease management.
Key words: *Trichoderma asperellum*, *Trichoderma harzianum*, *Fusarium oxysporum*, biological control, antagonistic activity

Özet
Fungal patojenler, tarımsal üretimi sınırlandıran başlıca etmenlerden biri olup, çok sayıda bitkide önemli verim ve kalite kayıplarına neden olmaktadır. Fungal hastalıkların mücadelesinde geleneksel olarak sentetik fungisitler ve diğer kimyasal pestisitler yoğun bir şekilde kullanılmaktadır. Bununla birlikte, bu

kimyasalların yoğun ve sürekli kullanımı; çevre kirliliği, hedef dışı organizmalar üzerindeki olumsuz etkiler, gıdalarda pestisit kalıntıları ve patojen popülasyonlarında dayanıklılığın gelişmesi gibi nedenlerle giderek artan endişelere yol açmaktadır. Bu nedenle, sentetik tarım kimyasallarına olan bağımlılığı azaltabilecek çevre dostu ve sürdürülebilir hastalık yönetimi stratejilerinin geliştirilmesi giderek daha fazla önem kazanmaktadır. Bu bağlamda, yararlı mikroorganizmaların kullanıldığı biyolojik mücadele, bitki hastalıklarının sürdürülebilir yönetimi açısından umut vadeden alternatif bir yaklaşım olarak öne çıkmaktadır.

Bu çalışmada, farklı konukçulardan elde edilen *Trichoderma* spp. izolatlarının, odunsu bitkilerde hastalık gelişimi ve verim kayıpları ile ilişkilendirilen fitopatojenik bir fungus olan *Fusarium oxysporum*'a karşı in vitro biyolojik mücadele potansiyelinin belirlenmesi amaçlanmıştır. Çalışmada değerlendirilen *Trichoderma* izolatları; elma rizosferinden elde edilen *T. asperellum* ile çilek, ceviz ve kayısıdan elde edilen *Trichoderma harzianum* izolatları ve ticari *T. harzianum* içerikli gübre ürününden elde edilen izolatı kapsamaktadır. İzolatların *F. oxysporum*'a karşı antagonistik aktiviteleri, in vitro koşullarda ikili kültür ve çift petri (double-plate) testleri kullanılarak araştırılmıştır. İkili kültür testlerinde, *Trichoderma* izolatlarının *F. oxysporum*'un radyal misel gelişimi üzerindeki etkileri değerlendirilmiş ve misel gelişiminin engellenme oranları belirlenmiştir. Ayrıca, antagonistik etkileşimlerde uçucu veya difüze olabilen antifungal metabolitlerin olası rolünü değerlendirmek amacıyla çift petri testleri gerçekleştirilmiştir.

Elde edilen sonuçlar, elma rizosferinden elde edilen *T. asperellum* izolatının, ikili kültür testlerinde *F. oxysporum*'un misel gelişimi üzerinde önemli düzeyde engelleyici etki gösterdiğini ortaya koymuştur. Bu sonuç, söz konusu izolatın güçlü bir antagonistik potansiyele sahip olduğunu ve biyolojik mücadele ajanı olarak daha ileri çalışmalar için umut vadeden bir aday olabileceğini göstermektedir. Buna karşılık, kontrol testlerinde uygulamalar arasında istatistiksel olarak önemli bir fark belirlenmemiştir. Genel olarak elde edilen bulgular, özellikle elma rizosferinden elde edilen *T. asperellum* olmak üzere, bazı *Trichoderma* izolatlarının *F. oxysporum*'un biyolojik olarak baskılanmasında potansiyel taşıdığını ve geleneksel kimyasal hastalık yönetimine sürdürülebilir alternatiflerin geliştirilmesine katkı sağlayabileceğini göstermektedir.

Anahtarlar kelimeler: *Trichoderma asperellum*, *Trichoderma harzianum*, *Fusarium oxysporum*, biyolojik mücadele, antagonistik aktivite, ikili kültür, in vitro

Introduction

Fusarium oxysporum is a widely distributed soilborne fungal pathogen and an important causal agent of vascular wilt and root and crown diseases in numerous economically important crops. The *F. oxysporum* species complex comprises both pathogenic and non-pathogenic strains, with pathogenic strains showing considerable host specialization and being classified into different formae speciales according to their host range. The pathogen has been reported from a wide range of plant species and is responsible for substantial yield and economic losses in agricultural production (Gordon, 2017; Edel-Hermann and Lecomte, 2019). Its ability to survive in soil and infect susceptible plants through the root system makes the management of *F. oxysporum* diseases particularly challenging. Therefore, the development of sustainable and effective biological control strategies against *F. oxysporum* is of considerable importance.

Among the microorganisms investigated for the biological control of *F. oxysporum*, *Trichoderma* spp. are considered important fungal antagonists because of their ability to rapidly colonize the rhizosphere and interact with plant pathogens. Their biocontrol activity can involve several mechanisms, including competition for nutrients and space, mycoparasitism, antibiosis, and the production of hydrolytic enzymes and secondary metabolites.

In addition to their direct antagonistic effects on pathogens, some *Trichoderma* strains can promote plant growth and enhance plant defense responses, contributing to overall plant health. Therefore, the selection and evaluation of effective *Trichoderma* isolates is an important step in developing sustainable management strategies for diseases caused by *F. oxysporum* (Harman et al., 2004; Benítez et al., 2004; Woo et al., 2023).

Materials And Methods

A phytopathogenic isolate of *Fusarium oxysporum* and three *Trichoderma* strains, namely *T. asperellum*, *T. harzianum*, and *T. harnatum*, were included in the in vitro experiments. The fungal

isolates had previously been identified and characterized using molecular methods. Prior to the assays, all fungal cultures were maintained on potato dextrose agar (PDA) and incubated at 26 ± 1 °C for 7 days. For each experiment, 5-mm-diameter mycelial plugs were excised from actively growing margins of the 7-day-old cultures and used as inoculum.

Dual Culture Assay

The dual-culture assay was performed following the procedure described by Rahman et al. (2009), with minor modifications. Briefly, 5-mm mycelial plugs were obtained from the actively growing margins of 7-day-old *Fusarium oxysporum* and *Trichoderma* cultures. A plug of each fungus was placed on the same PDA plate at an approximately 3-cm distance from each other. PDA plates inoculated only with *F. oxysporum* were used as pathogen controls. All plates were incubated at 26 ± 1 °C for 7 days, after which fungal growth was evaluated.

Isolation of Fungi

For the recovery of the fungal pathogen, symptomatic plant material exhibiting typical disease symptoms such as root, crown, stem, or fruit rot was collected from the relevant host plants. The samples were washed thoroughly with tap water and dried using sterile paper towels. Tissue sections approximately 2–3 mm in size were excised from the transition zone between healthy and diseased tissues. The sections were surface sterilized in 0.1% sodium hypochlorite (NaOCl) for 1–3 min, depending on the type and tenderness of the plant tissue, and subsequently rinsed with sterile distilled water. After drying, the disinfected tissue pieces were aseptically placed onto suitable isolation media and incubated under appropriate conditions. Fungal colonies emerging from the tissue pieces were transferred to fresh media and purified for further morphological and molecular characterization (Agrios, 2005).

Trichoderma isolates were recovered from rhizosphere soil collected from the root zones of the respective host plants, including apricot, walnut, apple, and strawberry. Soil samples were processed using standard procedures for the isolation of *Trichoderma* spp. from plant-associated soils. The resulting fungal colonies were purified and maintained on appropriate culture media until further identification and antagonism assays. The isolation procedure was based on methods previously described for the recovery of *Trichoderma* from soil and rhizosphere environments (Elad et al., 1981; Papavizas, 1985).

Molecular Identification of the Isolates

DNA Extraction

For molecular identification, the fungal isolates were cultivated on potato dextrose agar (PDA) at 24 °C for 10–12 days. Genomic DNA was subsequently extracted from the fungal material using the DNeasy Blood & Tissue Kit (Qiagen, Madison, WI, USA) following the manufacturer's instructions.

For the molecular characterization of *Trichoderma* isolates, the internal transcribed spacer (ITS) region was amplified using the ITS1 and ITS4 primers (White et al., 1990; Kroon et al., 2004). PCR amplification consisted of an initial denaturation step at 94 °C for 4 min, followed by 35 cycles of denaturation at 94 °C for 60 s, primer annealing at 58 °C for 60 s, and extension at 72 °C for 60 s. A final extension was performed at 72 °C for 5 min.

The RPB2 gene region was amplified for molecular identification of *Fusarium oxysporum* using the fRPB2-5F and fRPB2-7cR primer pair (Liu et al., 1999). The amplification program included an initial denaturation at 95 °C for 5 min, followed by 35 cycles consisting of denaturation at 95 °C for 1 min and annealing at 48 °C for 2 min. The temperature was then increased at a rate of 0.2 °C s^{-1} to 72 °C, followed by a 2-min extension at 72 °C. The reaction was completed with a final extension at 72 °C for 10 min.

PCR reactions were prepared in a total volume of 50 µL containing 5 µL of DNA template (approximately 10 ng), 26 µL of Thermo Scientific™ PCR Master Mix, 15 µL of nuclease-free water (Merck), and 2 µL of primer mixture. The primer sequences and amplification conditions are presented in Table 1.

Table 1. Primers and PCR conditions used for molecular identification of the fungal isolates.

Target gene region	Primer sequences	PCR protocol	Product length (bp)	References
ITS	ITS1: 5'TCCGTAGGTGAACCTGCGG3' ITS4: 5'TCCTCCGCTTATTGATATGC3'	94 °C-4 m 94 °C-60 s 58 °C-60 s 72 °C-60 s **35 cycle** 72 °C-5 m	590 bp	White et al. 1990; Kroon et al. 2004
RPB2	fRPB2-5F: GAYGAYMGWGATCAYTTYGG fRPB2-7cR: CCCATRGCTTGYTTRCCCAT	95 °C 5 m, 95 °C 1 m 48 °C 2 m 72 °C 2 m **35 cycle** 72 °C 10 m	989 bp	Liu et al. 1999

Agarose Gel Electrophoresis and PCR Product Selection

The amplified PCR products were analyzed by electrophoresis using a 1.5% agarose gel prepared in 1× TAE buffer (40 mM Tris-acetate and 1 mM EDTA, pH 8.0). For gel preparation, 1.5 g of agarose was dissolved in 100 mL of 1× TAE buffer by heating in a microwave oven. After cooling, 5 µL of Nucleic Acid Gel Staining Solution was added per 100 mL of gel solution and mixed thoroughly. The prepared agarose was poured into a horizontal electrophoresis tray and allowed to polymerize. Following electrophoresis, DNA bands were visualized using a UV transilluminator imaging system. PCR products showing bands of the expected size were selected and submitted for sequencing.

The ITS region was amplified from the *Trichoderma* isolates using the ITS1 and ITS4 primer pair, whereas the RPB2 region was amplified from the *Fusarium oxysporum* isolate using the fRPB2-5F and fRPB2-7cR primers. The resulting sequences were compared with reference sequences available in the National Center for Biotechnology Information (NCBI) GenBank database to confirm the molecular identities of the fungal isolates.

Statistical analysis

The antagonistic effects of the *Trichoderma* isolates on *Fusarium oxysporum* were determined using the dual-culture assay. Inhibition of pathogen growth was expressed as the percentage inhibition of radial growth (PIRG), calculated according to Skidmore and Dickinson (1976) as follows: PIRG (%) = [(C − T) / C] × 100, where C is the mean radial growth of the pathogen in the control plates and T is the mean radial growth measured in the presence of a *Trichoderma* isolate. Each treatment was performed in duplicate, and the mean values for pathogen growth and PIRG were calculated. As only two replicates were included per treatment, the data were summarized using descriptive statistics without performing inferential statistical tests.

Results and Discussion

Molecular identification of the fungal isolates

Molecular identification was performed using ITS sequences for the Trichoderma isolates, whereas the RPB2 region was used for the identification of the Fusarium isolates. PCR amplification produced products of the expected sizes for the target regions, and positive amplification products were selected for sequencing. The obtained sequences were compared with sequences deposited in GenBank to support the identification of the fungal isolates.

The antagonistic activities of the tested Trichoderma isolates against the target Fusarium species were evaluated using the dual-culture assay. Differences were observed among the Trichoderma isolates in their ability to suppress the radial mycelial growth of the tested pathogens. The percentage inhibition of radial mycelial growth (PIRG) was calculated based on the radial growth of the pathogens in the control plates and in the presence of Trichoderma isolates.

The antagonistic potential of the evaluated Trichoderma isolates against *Fusarium oxysporum* demonstrated notable variation among strains. Compared to the pathogen control (mean radial growth

of 36.5 mm), the application of Trichoderma isolates restricted pathogen mycelial growth to a range of 20.0–30.0 mm (Table 2).

Among all tested strains, isolate T-3 (*Trichoderma asperellum*), obtained from apple, exhibited the strongest biocontrol efficacy, achieving a 45.2% inhibition rate and suppressing mean pathogen growth to 20.0 mm. Substantial growth suppression was also recorded for T-4 (*T. harzianum*; 39.7% inhibition, 22.0 mm growth) and T-2 (*T. harzianum* from walnut; 24.7% inhibition, 27.50 mm growth).

In contrast, isolates T-1 (*T. harzianum* from apricot) and T-5 (*T. harnatum* from strawberry) displayed lower inhibitory activity, each yielding an inhibition rate of 17.8% (30.0 mm growth). Overall, all Trichoderma isolates successfully suppressed F. oxysporum development, with T-3 showing the highest antagonistic performance. This growth suppression is likely mediated by space and nutrient competition, mycoparasitism, and antifungal metabolite synthesis (Elad et al., 1981; Papavizas, 1985)

Table 2. Antagonistic activity of Trichoderma isolates against Fusarium oxysporum based on dual-culture assay.

Isolate no	Isolate source	Pathogen fungal growth (mm)	Trichoderma growth (mm)	Inhibition of radial growth (%)	Growth differences (T - P) (mm)
T-1	Apricot- *T. harzianum*	30,00	56,00	**17,8%**	26,50
T-2	Walnut-*T. harzianum*	27,50	56,50	**24,7%**	29,00
T-3	Apple- *Trichoderma asperellum*	20	59,50	**45,2%**	39,50
T-4	*Trichoderma harzianum*	22	60,00	**39,7%**	38,00
T-5	Strawberry- *T. harnatum*	30	57	**17,8%**	27,00
Control	*Fusarium oxysporum*	36,50	0,00	**0,0%**	-

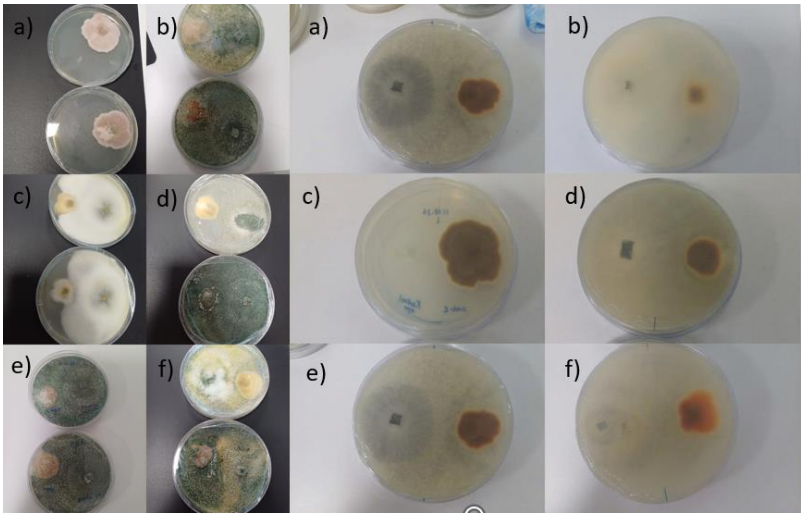


Figure 1. Dual-culture assays of *Fusarium oxysporum* against different Trichoderma isolates: a*) F. oxysporum* control, b) *Trichoderma harnatum* isolated from strawberry, c) *Trichoderma harzianum* derived from commercial fertilizer, d) *Trichoderma asperellum*

The antagonistic potential of *Trichoderma* spp. against *Fusarium* species has been widely demonstrated in previous studies. Several reports have shown that *T. harzianum*, *T. asperellum*, and other *Trichoderma* species can effectively restrict the mycelial growth of different *Fusarium* pathogens in dual-culture

assays. For example, *T. harzianum* has been reported to inhibit *Fusarium oxysporum* through competition for nutrients and space, as well as mycoparasitic interactions, while *T. asperellum* has also shown considerable antagonistic activity against different *Fusarium* species (Bunbury-Blanchette and Walker, 2019; Modrzewska et al., 2022).

Conclusion

The findings of this study revealed variation among the tested Trichoderma isolates in their ability to inhibit the growth of *Fusarium oxysporum*. The antagonistic interactions observed under in vitro conditions indicate that certain Trichoderma isolates could be promising candidates for the biological management of *F. oxysporum*. Such differences in inhibitory performance may be associated with the specific biological characteristics and antagonistic mechanisms of individual Trichoderma isolates.

Nevertheless, the results obtained in vitro should be interpreted with caution, as they do not necessarily reflect the biocontrol performance of Trichoderma under greenhouse or field conditions. The effectiveness of Trichoderma against *F. oxysporum* may be affected by several factors, including environmental conditions, interactions with the host plant and native microbial community, variability within pathogen populations, formulation characteristics, and the timing and method of application. Therefore, further experiments under controlled greenhouse and field conditions are necessary to determine the consistency and practical effectiveness of the selected Trichoderma isolates against *F. oxysporum*.

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IMPORTANCE OF WHEAT PRODUCTION AND EVALUATION OF PLANT PROTECTION PROBLEMS IN SİVAS

SİVAS İLİNDE BUĞDAY ÜRETİMİNİN ÖNEMİ VE KARŞILAŞILAN BİTKİ KORUMA SORUNLARININ DEĞERLENDİRİLMESİ

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Abstract
Wheat (*Triticum aestivum* L.) is a strategically important crop for human nutrition and food security. Root and crown diseases are among the major biotic constraints limiting wheat yield and quality. This review aims to evaluate the principal pathogens associated with root, crown and basal stem diseases of wheat, their symptoms, conditions influencing disease development, and integrated management approaches. Major pathogens include *Fusarium* spp., particularly *F. pseudograminearum* and *F. culmorum*, *Bipolaris sorokiniana*, *Rhizoctonia* species, *Gaeumannomyces tritici* and *Oculimacula* species. Oomycetes belonging to the genera *Pythium* and *Globisporangium* can also cause root rot. Infections may result in root and crown necrosis, poor plant growth, reduced tillering, premature senescence and impaired grain filling. Disease occurrence and severity are associated with soil temperature and moisture, inoculum density, cultivar susceptibility, crop rotation and other agronomic practices. Water stress, in particular, can exacerbate the adverse effects of certain crown rot diseases on yield. Because symptoms may overlap and multiple pathogens may coexist, reliable diagnosis requires field observations supported by morphological and molecular investigations. Healthy seed, appropriate cultivar selection, crop rotation tailored to the target pathogen, crop residue management and agronomic practices that reduce plant stress constitute the main components of integrated management. In conclusion, determining regional pathogen distribution and developing diagnosis-based management programmes are important for reducing losses caused by root and crown diseases in wheat.
Keywords: Wheat, root rot, crown rot, soilborne pathogens, disease diagnosis, integrated management.

Özet
Buğday (*Triticum aestivum* L.), insan beslenmesi ve gıda güvenliği açısından stratejik öneme sahip bir kültür bitkisidir. Buğday üretiminde verim ve kaliteyi sınırlandıran biyotik faktörler arasında kök ve kök boğazı hastalıkları önemli bir yer tutmaktadır. Bu derlemede, buğdayda kök, kök boğazı ve sap dibi hastalıklarıyla ilişkili başlıca etmenlerin, hastalık belirtilerinin, gelişimi etkileyen koşulların ve entegre mücadele yaklaşımlarının değerlendirilmesi amaçlanmaktadır. Başlıca patojenler arasında Fusarium spp., özellikle *F. pseudograminearum* ve *F. culmorum*, *Bipolaris sorokiniana*, *Rhizoctonia* türleri, *Gaeumannomyces tritici* ve *Oculimacula* türleri bulunmaktadır. Ayrıca *Pythium* ve *Globisporangium* cinslerine ait oomyceteler de kök çürüklüklerine neden olabilmektedir. Bu etmenlerin oluşturduğu enfeksiyonlar köklerde ve kök boğazında nekroz, zayıf gelişme, kardeşlenmede azalma, erken kuruma ve tane dolumunda yetersizlikle sonuçlanabilmektedir. Hastalıkların ortaya çıkışı ve şiddeti; toprak sıcaklığı ve nemi, inokulum yoğunluğu, çeşit duyarlılığı, ekim nöbeti ve diğer yetiştirme uygulamalarıyla ilişkilidir. Özellikle su stresi, bazı kök boğazı çürüklüklerinin verim üzerindeki olumsuz etkisini artırabilmektedir. Belirtilerin benzerliği ve birden fazla etmenin birlikte bulunabilmesi nedeniyle güvenilir tanıda saha gözlemlerinin morfolojik ve moleküler incelemelerle desteklenmesi önem taşımaktadır. Entegre mücadelede sağlıklı tohumluk kullanımı, uygun çeşit seçimi, hedef patojene göre planlanan ekim nöbeti, bitki artıklarının yönetimi ve bitki stresini azaltan yetiştirme uygulamaları temel bileşenlerdir. Sonuç olarak, bölgesel etmen dağılımının belirlenmesi ve tanıya dayalı mücadele programlarının geliştirilmesi, buğdayda kök ve kök boğazı hastalıklarından kaynaklanan kayıpların azaltılması açısından önemlidir.
Anahtar kelimeler: Buğday, kök çürüklüğü, kök boğazı çürüklüğü, toprak kökenli patojenler, hastalık tanısı, entegre mücadele.

GİRİŞ

Buğday (Triticum aestivum L.), dünya genelinde ekim alanı ve üretim miktarı bakımından ilk sırada yer alan önemli bir kültür bitkisidir. İnsan beslenmesinde temel besin kaynağı olma özelliğindedir. Dünya'nın ve Türkiye'nin neredeyse her bölümünde üretimi yapılan buğday; gerek çok büyük üretici kitlesini ilgilendirmesi, gerekse insanların temel gıdası olan ekmeğin hammaddesini oluşturması bakımından oldukça önemli bir üründür (Kızılaslan, 2004). Buğday üretiminde çeşitli yöntemlerle artış sağlanabilmesine karşın, önemli ürün kayıplarına yol açan çok sayıda faktör de bulunmaktadır. Buğday hastalıkları ve özellikle bunlardan da kök ve kök boğazı hastalıkları buğday verimini sınırlayan en önemli faktörler arasında yer almaktadır.

Türkiye'de kışlık buğdayda %43 (Hekimhan ve ark., 2004), Orta Anadolu Platosu'ndaki (OAP) makarnalık buğdayda ise %54 oranında kayıplar rapor edilmiştir (Bağcı ve ark., 2001). Aktaş ve ark. (1999), kök ve kök boğazı çürüklükleri sonucunda kışlık tahıllarda %36 oranında hastalık yoğunluğu bildirmiştir. Kışlık buğdayın ana ürün olduğu Orta Anadolu Platosu, yıllık 250-500 mm yağış alan 10 milyon hektarlık tarım arazisini kapsamaktadır (Benli ve ark., 2007). Dünyada hastalıklar nedeniyle oluşan verim kayıplarının; Amerika'nın Pasifik Kuzeybatı (PNW) bölgesindeki kışlık buğdayda %35'e (Smiley, 2005), Avustralya'da %25-58'e ulaştığı, hastalığın bazı durumlarda %89'a kadar kayıp yaşatabildiği (Klein, 1991; Chakraborty ve ark., 2010) ve Tunus'ta %49'a vardığı (Chekali, 2016) bildirilmiştir.

Buğdayda kök ve kök boğazı hastalıklarına neden olan en yaygın etmenler Fusarium spp. ve Rhizoctonia spp. olup bunların yanı sıra Drechslera sorokiniana, Pythium graminicolum, Pseudocercosporella herpotrichoides ve Ophiobolus graminis sıklıkla görülen patojenlerdir (Aktaş, 2001). Buğdayda görülen fungal hastalıklar; tohum ve başak hastalıkları, yeşil aksam ve yaprak hastalıkları ve kök, kökboğazı ve sap hastalıkları olmak üzere sınıflandırılabilir. Buğday bitkilerinin kök, kökboğazı ve sap kısmında yanıklık veya çürüklük benzeri simptomlara neden olan önemli fungal etmenler; Bipolaris, Fusarium, Gaeumannomyces, Pseudocercosporella, Pythium ve Rhizoctonia cinslerine bağlı fungus türleridir.

Biyotik stres faktörleri arasında; kışlık tahıllarda kök, kök boğazı ve sap çürümelerine neden olan Fusarium türleri, dünya çapında tahıl odaklı tarım sistemlerinin hakim olduğu hemen her yerde görülmektedir (Burgess ve ark., 2001). Hastalığa öncelikle Fusarium culmorum, F. pseudograminearum ve F. graminearum neden olmaktadır. Fusarium türlerinin genomik yapısı ve konakçıya özelleşme mekanizmaları üzerine yapılan araştırmalar, bu patojenlerin çevresel koşullara hızlı adapte olabildiğini ve virülans faktörlerinin genomik düzeyde çeşitlilik gösterdiğini ortaya koymaktadır (Ma ve ark., 2013). Bu durum, Sivas ili buğday ekim alanlarında saptanacak patojen profillerinin ve bunların patojenisite düzeylerinin belirlenmesinin, bölgesel mücadele stratejileri açısından önemini pekiştirmektedir.

Rhizoctonia cinsi dünyanın her yerinde ve ülkemizde yaygın olarak bulunan önemli toprak patojenlerinden birisidir. Fungus kendi içerisinde çeşitlilik gösteren, geniş ve kompleks bir gruptur (Carling ve Summer, 1992). Çevresel koşullara yüksek oranda adaptasyon göstermesi nedeniyle tüm dünyaya yayılmıştır ve dünyada ekonomik açıdan önemli 200'ü aşkın bitkide yıllık ortalama %20'den fazla ürün kaybına neden olmaktadır (Clarkson ve Cook, 1983; MacNish ve Neate, 1996; Cromey ve ark., 2002).

Rhizoctonia, dünya genelinde tarım alanlarında yaprak ve kök çürüklüğü hastalıklarına neden olan, ekonomik açıdan en önemli bitki patojenlerinden biridir. Rhizoctonia türleri sklerotları ile toprakta uzun süre canlı kalabilmektedir. Ayrıca saprofitik rekabetçiliği, patojenik özellikleri, çok hızlı gelişimi ve geniş konukçu dizisi nedeniyle sorun oluşturan bir cins olarak bilinmektedir. Bu nedenle hastalığın kimyasal mücadelesi zordur ve ancak sınırlı alanlarda kısmen başarılı olabilmektedir (Mohammadi ve ark., 2003).

Bipolaris sorokiniana arpa ve buğday bitkilerinde önemli bir patojen olup, ülkemizde özellikle iç kesimlerde ve dünyada ılıman iklim kuşağında önemli ekonomik kayıplara yol açmaktadır. Yapılan bir araştırmada, Orta Anadolu Bölgesi'nde hastalığın arpa ekim alanlarının 1/3'ünün bu hastalıkla bulaşık olduğu belirlenmiştir (Aktaş ve Tunalı, 1994). Göbelez (1952) ise B. sorokiniana'nın Konya Ereğli'sinde tarlalarda %50 yaygınlıkta olduğu ve farklı tarlalardan alınan arpa bitkilerinin %15-40 arasında bu patojenle bulaşık olduğunu belirlemiştir. B. sorokiniana'nın konidioforları koyu kahverengi, kısa ve çoğunlukla tek veya küçük gruplar halinde düz veya kıvrık, konidiosporları ise 3-10 bölmelidir. Hastalık etmeni bir yıldan diğerine tohumlarla ve tarlada kalan hastalıklı bitki artıklarıyla geçmektedir. Pseudocercosporella herpotrichoides'in vejetatif miselleri genellikle sarı ile kahverengi uzun hücrelere sahip olup, stroma miselleri ise çok hücreli kalın duvarlı ve poligonaldir. Bitkide yaralar içinde fungusun

miselleri bulunur. Sporları çoğunlukla 5-7 bölmeli olup, PDA besiyerinde az sayıda da olsa gelişebilen, ince uzun yapıdadır. Fungus enfekteli bitki artıklarında yaşamını sürdürür. İlkbahar yağışlarında fungusun hifleri genç yaprak kınlarına ulaşır ve yaprakları enfekte eder. Buğday ekiminin yoğun olduğu bölgelerde patojen profilinin saptanması, o bölgede alınacak kültürel tedbirler ve mücadele stratejilerine yol gösterebilmektedir.

Yapılması planlanan yüksek lisans tez çalışması kapsamında Sivas ili ve ilçelerindeki buğday ekim alanlarında görülebilecek kök, kökboğazı ve sap çürüklüğü hastalığı etmenlerinin belirlenmesi, hastalıkların yaygınlık ve bulunuş oranlarının ortaya çıkarılması hedeflenmektedir.

YÖNTEM

Sivas ili ve ilçelerine bağlı buğday ekim alanları incelenmiştir. Sörvey çalışmasında bitkilerin büyüme dönemleri esas alınacak ve buğdaylar süt olum dönemine ulaştığında (Zadoks skalasına göre 75. dönem; Zadoks ve ark., 1974) ilk sörvey çıkışı yapılmıştır. Bu amaçla söz konusu buğday tarlalarının farklı bölgelerinden rastgele seçilen buğday bitkileri kökleri ile birlikte alınarak etiketlenmiş, o tarlaya ait bilgiler ve alındığı tarihler not edilerek plastik torbalar içerisinde laboratuvara getirilmiştir. Tarlalara ait GPS konum bilgileri de alınmıştır. Laboratuvar ortamına getirilen materyaller, simptomatolojik inceleme ve izolasyon aşamalarına kadar canlılığını koruması amacıyla +4°C'de buzdolaplarında muhafaza edilmiştir. Araziden getirilen bitki materyalleri çeşme suyu altında dikkatlice yıkanarak toprak kalıntılarından arındırılmış; kök ve kök boğazı bölgeleri yaprak kınlarından temizlenerek incelemeye hazır hale getirilmiştir. Tarlalardan toplanan bitkiler incelenmeye alınmıştır. Bitkilerdeki kök ve kök boğazı semptomları, Wildermuth ve McNamara (1994) tarafından geliştirilen hastalık değerlendirme skalasına göre değerlendirilecektir.

Hastalık çıkışı hesaplamasında simptomatolojik olarak incelenen 100 bitkiden sağlıklı olanların sayısı çıkarılacak ve oluşan fark ile hasta bitkilerin oranı belirlenecektir. Hastalık şiddetini belirlemek amacıyla Townsend ve Heuberger formülü uygulanacaktır (Karman, 1971):

Hastalık Şiddeti (%) = [Σ (Skala Değeri × Skala Değerine Dahil Olan Bitki Sayısı) / (Toplam Bitki Sayısı × En Yüksek Skala Değeri)] × 100

Bu şekilde her bir tarla için hesaplanan hastalık çıkışı ve hastalık şiddeti değerlerinin ortalamaları alınarak, Sivas ve ilçelerdeki ortalama değerler elde edilecektir.

İnfekteli buğday bitkileri simptomatolojik olarak incelendikten sonra kök, kök boğazı ve sap bölgelerinden standart mikolojik izolasyonlar yapılacaktır. Elde edilen izolatlar cins düzeyinde ayırt edilecek, bu fungusların izole edilme oranları hesaplanacaktır. İzolasyonlar sonucunda tanısı yapılan fungus türlerinin patojenisite çalışmaları Liddell ve ark. (1986) ile Wildermuth ve McNamara (1994)'ya göre yapılacaktır. Patojenisite çalışmaları 3 tekerrürlü olarak Sivas Bilim ve Teknoloji Üniversitesi (SBTÜ) iklim odalarında yürütülecektir.

ARAŞTIRMA BULGULARI VE TARTIŞMA

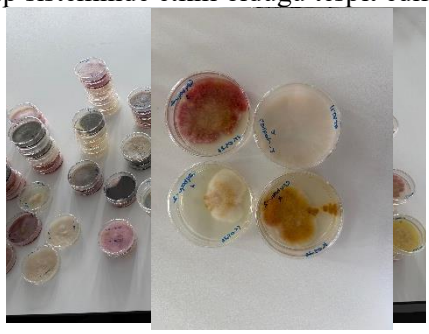
Sivas ili ve ilçelerindeki buğday ekim alanlarında gerçekleştirilen sörvey çalışmaları sonucunda, bitkilerin kök, kök boğazı ve sap bölgelerinde kahverengi lezyonlar, nekrotik çökmeler, iletim demetlerinde esmerleşme gibi tipik kök ve kök boğazı çürüklüğü simptomları gözlemlenmiştir. Aynı zamanda sörvey esnasında bitkilerde sarı pas ve septorya yaprak lekesi hastalıklarının bulgularına da rastlanmıştır.

Bitkilerin süt olum döneminde (Zadoks 75) yapılan incelemelerde, incelenen tarlaların büyük bir kısmında farklı düzeylerde hastalık çıkışı ve şiddeti saptanmıştır. Araziden toplanıp laboratuvara +4°C'de muhafaza edilerek getirilen örneklerin çalışmaları sonucunda fungal patojenlere rastlanmıştır.

Elde edilen bulgular, dünya genelinde ve Türkiye'nin tahıl üretim merkezlerinde kök ve kök boğazı çürüklüğü etmenlerinin yaygınlığını ortaya koyan önceki çalışmalarla büyük ölçüde paralellik göstermektedir. Kışlık buğdayda kök ve kök boğazı hastalıklarının ülkemizde %43 (Hekimhan ve ark., 2004), Orta Anadolu Platosu'nda ise yüksek oranlarda verim kayıplarına yol açabildiği bilinmektedir. Özellikle Fusarium türlerinin (F. culmorum, F. pseudograminearum ve F. graminearum) tahıl üretiminin olduğu alanlarda evrensel bir sorun olduğu ve bu türlerin genetik adaptasyon yetenekleri ile virülans çeşitliliğinin yüksek olduğu bilinmektedir. Sivas ili ekim alanlarında saptanan patojen profilleri, bu adaptasyon yeteneğinin bölgesel düzeydeki yansımasını açıkça göstermektedir.

Toprak patojeni olarak geniş bir konukçu dizisine sahip olan Rhizoctonia cinsinin, çevresel koşullara yüksek adaptasyon göstererek ekonomik kayıplara neden olduğu literatürle uyumludur (Carling ve

Summer, 1992; Clarkson ve Cook, 1983). Benzer şekilde, ılıman iklim kuşağında ve iç kesimlerde arpa ve buğdayda önemli kayıplara yol açan Bipolaris sorokiniana'nın (Aktaş ve Tunalı, 1994) Sivas koşullarında da buğday kök ve sap sisteminde etkili olduğu tespit edilmiştir.



Şekil 1. Buğday örneklerinden izole edilen kök ve kök boğazı patojeni fungus kültürlerinin genel görünümü.

SONUÇ

Buğday, Türkiye'de en çok yetiştirilen tahıl ürünlerinden biridir. Bu çalışma sonucu, buğday kök hastalıklarının, buğday üretimi için potansiyel bir tehdit olarak ortaya çıkan en önemli hastalıklardan biri olduğunu göstermiştir. Buğday kök hastalıklarının yaygınlık, bulunma oranı ve şiddeti Sivas ilinin bölgelerinde değişiklik göstermesine rağmen, hastalık şiddeti, bulunma oranına göre genellikle yaygın olarak belirlenmiştir. Sivas ilindeki hastalıklar, yüksek hastalık bulunma oranı ve şiddeti, muhtemelen çevresel koşulların varlığı, iklim değişikliği ve kültürel uygulamalardaki hatalardan kaynaklanmıştır. Buğday kök ve kökboğazı hastalıklarının bulunma oranı ve şiddeti üzerine etkili olan iklimsel ve biyofiziksel faktörlerin ayrıntılı araştırılmasına ihtiyaç vardır.

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HASSAS HAYVANCILIK: SÜRDÜRÜLEBİLİR HAYVANCILIĞI DESTEKLEMEYE VE ÇEVRESEL RİSKLERİ AZALTMAYA YÖNELİK BİR YAKLAŞIM

PRECISION LIVESTOCK FARMING: AN APPROACH TO SUPPORTING SUSTAINABLE LIVESTOCK FARMING AND REDUCING ENVIRONMENTAL RISKS

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Özet
Hayvancılığı; ekonomik, sosyal ve çevresel olarak daha sürdürülebilir bir hale getirmek, yönetim stratejilerini desteklemek için; hayvanlardan iyi bir verimlilik ve üreme performansı elde etmek, hayvan sağlığı ve refahını korumak, hayvansal üretim sürecinde birim başına çevresel etkiyi azaltmak bir zorunluluktur. Hassas hayvancılık (Precision livestock farming, PLF), sürdürülebilir bir hayvancılığın bu amaçlarına ulaşabilmek için iyi bir potansiyele sahiptir. Sürdürülebilir bir hayvansal üretim sistemine geçiş yolunda yetiştiricilere büyük fırsatlar sunabilecek bir araç olarak hassas hayvancılık, hayvanların yaşamını iyileştirmeye odaklanan, gerçek zamanlı olarak hayvanları otomatik izleme ve yönetim sistemi aracılığıyla yetiştiricilerin hemen harekete geçebilmesine imkan sunan, aktif bir şekilde sürece dahil olabildikleri karar destek sistemlerini hayata geçiren, hayvan sağlığı ve refahı, ürün veriminin ve çevresel etkilerinin izlenmesi ve iyileştirilmesini mümkün kılan bir yaklaşımdır. Bu çalışmada, hassas hayvancılık uygulamalarının hayvansal üretim sürecinden kaynaklanabilen çevresel etkiyi azaltmak ve çevre dostu sürdürülebilir bir hayvancılık için potansiyelini ele almak ve bu konudaki genel tartışmaya katkıda bulunmak amaçlandı.
Anahtar Kelimeler: Hassas Hayvancılık, Sürdürülebilirlik, Çevre Etkileri, Hayvan Sağlığı, Hayvan Refahı.

Abstract
To make livestock farming more economically, socially, and environmentally sustainable and to support management strategies, it is essential to achieve good productivity and reproductive performance in animals, protect animal health and welfare, and reduce the environmental impact per unit in the livestock production process. Precision livestock farming (PLF) holds great potential for achieving these goals of sustainable livestock farming. As a tool that can offer farmers significant opportunities on the path to transitioning to a sustainable livestock production system, is an approach that focuses on improving animal welfare, enables producers to take immediate action through real-time automated animal monitoring and management systems, implements decision-support systems that actively involve producers in the process, and facilitates the monitoring and improvement of animal health and welfare, production efficiency, and environmental impacts. The aim of this study was to examine the potential of sustainable livestock farming practices to reduce the environmental impact that may arise from the livestock production process, to explore their potential for environmentally friendly and sustainable livestock farming, and to contribute to the broader discussion on this topic.
Key Word: Precision Livestock Farming, Sustainability, Environmental Impacts, Animal Health, Animal Welfare.

Giriş

Hayvancılık küresel boyutta dinamik bir sektör olup, doğal kaynaklar, arazi ve su kullanımı, karbon kısıtlamaları, çevre ve hayvan sağlığına dair tüm düzenlemelerden etkilenmektedir. Hassas hayvancılık uygulamalarının (Precision livestock farming, PLF), hayvansal üretime aktarılması ile; verimlilik, hayvan refahı, sağlığı ve sürü yönetimi gibi konularda gelişmeler sağlanmasının yanı sıra hayvansal üretim sürecinden kaynaklanabilen çevresel etkiyi minimize etmek gibi ikincil kazanımlarda sağlanmaktadır (Berckmans, 2017; Fournel et al., 2017; Tullo et al., 2019; Lovarelli et al. 2020; Kahraman ve Yılmaz, 2024).

Sürdürülebilir bir hayvansal üretim sistemine geçiş yolunda hassas hayvancılık, yetiştiricilere büyük fırsatlar sunabilecek bir araçtır. Hassas hayvancılık, hayvanların yaşamını iyileştirmeye odaklanan, gerçek zamanlı olarak hayvanları otomatik izleme ve yönetim sistemi aracılığıyla yetiştiricilerin hemen

harekete geçebilmesine imkan sunmaktadır. Hassas hayvancılık uygulamalarının benimsenmesi ile, hayvanlarının sağlığı ve refahının güvence altına alınması, verimlilik ve üreme performansının artırılması, hayvan başına verime karşılık çiftliklerin çevresel etkilerin azaltmasına katkı sağlanabildiği bildirilen birçok çalışma bulunmaktadır (Berckmans, 2014; Fournel et al., 2017; Tullo et al., 2019; Lovarelli et al. 2020; Kahraman ve Yılmaz, 2024).

Bu çalışmada, hassas hayvancılık uygulamalarının hayvansal üretim sürecinden kaynaklanabilen çevresel etkiyi azaltmak ve çevre dostu sürdürülebilir bir hayvancılık için potansiyelini ele almak ve bu konudaki genel tartışmaya katkıda bulunmak amaçlandı.

Hassas Hayvancılık

Hassas Hayvancılık (PLF), hayvan üretimini otomatik olarak izlemek, modellemek ve yönetmek için süreç mühendisliği prensip ve tekniklerinin hayvancılığa uyarlanması ile geliştirilmiş bir sistemdir (Berckmans, 2017; Fournel et al., 2017; Tullo et al., 2019). Hassas hayvancılık, hayvancılık bilgi teknoloji ve yönetim süreçlerini kullanılarak; hayvanların verimliliği ve performansı optimize etmek, kayıpları azaltmak, ürün kalitesini artırmak, mevcut kaynakları iyi şekilde kullanmak ve yoğun üretim sistemi içerisinde her bir hayvanın ihtiyacını daha iyi bir şekilde karşılamak için geliştirilen yeni bir araç olarak görülmektedir (Berckmans, 2017; Tullo et al., 2019; Lovarelli et al. 2020; Kahraman ve Yılmaz, 2024).

Hayvansal üretimde küresel boyutta; teknolojik gelişmelere dayanan hassas hayvancılık uygulamaları itici güç olarak kullanılmaktadır (Berckmans, 2014; Berckmans, 2017; Tullo et al., 2019; Losacco et al., 2025). Hassas hayvancılık, genel olarak çevresel sürdürülebilirlik, hayvan refahı ve kaynak kullanım verimliliği gibi acil endüstri sorunlarına da odaklanmaktadır. Bireysel hayvan yönetimini geliştirmek üzere tasarlanmış yapay zeka, nesnelerin interneti, bulut bilişimi, büyük veri analitiği ve makine öğrenimi tabanlı sistemlerin hayvansal üretim süreçlerine entegre edildiği hayvan odaklı bir yaklaşımıdır (Tedeschi et al., 2026; Vlaicu et al., 2024; Losacco et al., 2025). Hassas hayvancılık uygulamaları bütün olarak; sürdürülebilirlik, hayvan davranışı, sağlığı, refahı ile barınak koşulları gibi çok boyutlu hayvansal üretim yönlerini, yönetim stratejileri ve teknoloji kullanımını da kapsamaktadır (Place and Mitloehner, 2014; Tullo et al., 2019; Lovarelli et al. 2020).

Hassas hayvancılık uygulamaları; hayvanların biyolojik tepkilerinin tanımlanması, sınıflandırılması, hayvan davranışları, seslendirmeleri ve hayvan-çevre etkileşiminden kaynaklanan parametrelerin belirlenmesi, hayvanların biyolojik tepkilerinin modellemesi, hayvanların izlenmesi ve yönetimsel kararların alınması gibi adımları içermektedir (Berckmans, 2017; Fournel et al., 2017; Tullo et al., 2019; Kahraman ve Yılmaz, 2024). Bu amaçla; kamera, mikrofon, sensörler, internet bağlantıları ve bulut depolama gibi teknolojiler kullanılarak, çiftlikteki hayvanların fizyolojik, davranışsal parametreleri ile çevresel değişkenlerin otomatik olarak izlenmesi, kontrol edilmesi ve gerekli müdahalenin yapılması sağlanabilmektedir (Berckmans, 2014; Berckmans, 2017; Tullo et al., 2019; Kahraman ve Yılmaz, 2024). Bu sistem basamakları öncelikle sürekli olarak hayvanların ve ortamın takip edilmesi, verilerin toplanması, verilerin depolanması, hayvan sağlığı ve refahı ölçüm kriterlerini değerlendiren modellerin kullanılarak ölçümlerin yorumlanması ve her bir işlem çıktısı için hedef değerler doğrultusunda belirlenmiş kontrol sistemlerinin devreye sokulduğu bir iş akışını içermektedir (Fournel et al., 2017; Tullo et al., 2019; Kahraman ve Yılmaz, 2024).

Hassas hayvancılık uygulamaları sayesinde çiftliklerde; hayvan verimi, endemik hastalıkları, barınaklarının fiziksel ortamı gibi unsurlar doğrudan ve gerçek zamanlı izlenerek hayvanlar için uygun koşulların sağlanması ve bu yolla gelecekte sürdürülebilir bir hayvancılığa ulaşılmasının mümkün olabileceği bildirilmektedir (Berckmans, 2014; Fournel et al., 2017; Tullo et al., 2019; Kahraman ve Yılmaz, 2024). Hassas hayvancılık, gübre yönetimi, su tüketimi, yenilenebilir enerji kaynakları gibi çevresel etkilerin azaltılmasından sorumlu kaynak yönetiminin teşvik edilmesine kadar birçok alanda sürdürülebilir uygulamaların geliştirilmesine aracılık etmektedir (Vlaicu et al., 2024; Tedeschi et al., 2026; Losacco et al., 2025).

Çevresel riskleri azaltmaya ve sürdürülebilirliği desteklemeye yönelik hayvancılık stratejileri

Hayvancılık sektörü; arazi, su ve enerji gibi sınırlı doğal kaynaklar için giderek daha fazla rekabet etmektedir. Hava, su ve toprak kalitesi üzerinde etkiler yaratmaktadır. Bu etkinin, fosil yakıt kullanımı, ormansızlaşmadan kaynaklanan karbondioksit emisyonu, geviş getiren hayvanların gübresinden ve bağırsak fermantasyonundan kaynaklanan metan emisyonu ve yetiştirme sırasında gübre

uygulamasından kaynaklanan azot oksit emisyonuna katkılar şeklinde birçok yolla gerçekleştiği bildirilmektedir. Hayvancılığın, küresel sera gazı emisyonlarının yaklaşık %18'inden sorumlu olduğu bildirilmektedir (de Vries and de Boer, 2010; Gerber et al., 2013; Kaufmann, 2015; Tullo et al., 2019; Lovarelli et al. 2020; Şeremet Tuğalay ve Güler, 2022).

Barınaklarda mikro klima üzerinde kontrol sağlamaya olanak tanıyan hassas hayvancılık uygulamaları; hayvan sağlığı ve refahı ile, hayvancılığın çevresel sürdürülebilirliğine ulaşmak için iyi bir yaklaşım olarak önerilmektedir (Berckmans, 2014; Berckmans, 2017; Fournel et al., 2017). Bu ve benzeri hassas hayvancılık uygulamalarının çiftliklerde yaygınlaştırılması, hayvansal üretim süreçlerinden kaynaklanan çevresel kirleticilerin başında gelen havadaki sera gazı (GHG) ve amonyak (NH_3) emisyonlarında, su kaynaklarındaki nitrat ve antibiyotik kirliliğinde, topraktaki fosfor, antibiyotik ve ağır metal düzeylerinde azalma sağlanabildiği bildirilmektedir (Tullo et al., 2019; Kahraman ve Yılmaz, 2024).

Lovarelli et al. 2020, tarafından yürütülen bir çalışmada; sağlık, hayvan performansı ve üretim gibi hayvancılığın temel konuların sürdürülebilirliğin üç temel unsurunun bağlantıların kesiştiği alanın hassas hayvancılığı tanımladığı bildirilmektedir. Hassas hayvancılık uygulamalarının hayvancılık üretiminin sürdürülebilirliğine, olumlu etkileri olduğu ve ekonomik, sosyal, çevresel alanlardan birine müdahale edilmesi ile diğer alanların da etkilendiği vurgulanmaktadır. Hayvanların sağlık koşullarının iyileştirilmesi, ilaç maliyetlerini düşürmeyi, hayvan refahını iyileştirmeyi, üretim kayıplarını önlemeyi ve üretimi artırmayı aynı zamanda çevresel, ekonomik ve sosyal sürdürülebilirliğini de iyileştirmeyi sağladığı ve bu durumun ise, hassas hayvancılık ve sürdürülebilirlik arasındaki en umut verici bağlantıyı ortaya koyduğu bildirilmektedir (Lovarelli et al. 2020).

Hayvancılığın çevresel etkilerini azaltmak amacıyla temelde hayvancılık sisteminin yoğunlaştırılması için yapısal değişiklikler, teknik ve yönetimsel müdahaleler yapılmaktadır. Bu amaçla; üretim verimliliğinin, yetiştirmenin ve hayvan sağlığının iyileştirilmesi; gübredeki besin maddelerini ve enerjiyi dönüştürüp geri kazanmak için gübre yönetimi uygulamalarının kullanılması; yem gibi düşük emisyonlu girdilerin temin edilmesi; amino asitler, enzimler ve fitobiyotikler gibi bağırsak düzenleyici ürünlerin yem katkı maddesi olarak kullanılması, yeni teknoloji ve hassas hayvancılık uygulamalarının benimsenmesi gibi stratejiler hayvancılıkta sürdürülebilirliği sağlayacak çözüm önerileri arasında sayılmaktadır (Kaufmann, 2015; Tullo et al., 2019; Lovarelli et al. 2020).

Hayvan sağlığının iyileştirilmesi ve hayvanlardaki hastalık ve ölüm oranlarının azaltılması; karbon ayak izini azaltılması, bağırsak fermantasyonundan ve hayvan gübresinden kaynaklanan metan (CH_4) ve azot oksit (N_2O) emisyonlarını azaltılması potansiyeline sahip olduğu bildirilmektedir (de Vries and de Boer, 2010; Van Hertem et al., 2016; Galioto et al., 2017; Tullo et al., 2019; Kahraman ve Yılmaz, 2024). Ancak, farklı hayvancılık sistemleri, türler ve iklimler arasında değişebilen koşullarda genel sürdürülebilirlik sağlanabilmesi için, hiçbir önlem tam olarak tek başına emisyon azaltma potansiyel sahip olmadığından, en iyi sonuca ulaşmak için mevcut seçeneklerin birlikte ve seçilen bir kombinasyon şeklinde uygulanmasının faydalı olacağı da vurgulanmaktadır (Leinonen and Kyriazakis, 2016; Llonch et al., 2017; Grossi et al., 2019).

Uygulamada Karşılaşılan Bazı Riskler ve Zorluklar

Hassas hayvancılık, hayvan sağlığı ve refahını sürekli ve gerçek zamanlı olarak izlemek üzere tasarlanmıştır. Hayvancılığın çevresel etkileri ile mücadele temel hedefleri arasında değildir (Tullo et al., 2019). Ancak, bazı araştırmacıların bu perspektiften gerçekleştirdikleri analizleri hassas hayvancılığın çevresel etkilere yönelik kazanımları sağladığını doğrulanmaktadır. Henüz sürdürülebilirlik unsurları için geliştirilmiş özel yöntemleri kapsayan hassas hayvancılık uygulamaları üzerine araştırmalar sınırlı düzeydedir ve daha fazla çalışmaya ihtiyaç vardır (de Vries and de Boer, 2010; Place and Mitloehner, 2014; Kaufmann, 2015; Tullo et al., 2019; Lovarelli et al. 2020; Şeremet Tuğalay ve Güler, 2022).

Araştırmacılar ve üreticiler arasında yakın işbirliği kurulması gerekliliği ile çoğu çiftçi ve diğer paydaşların, karmaşık modelleri ve teknolojileri etkili bir şekilde kullanmak için eğitilmesi ve bu teknolojilerin yaygınlaştırılması, enerji, internet ekipman maliyeti ve temini gibi konunun ekonomik boyutları ile etik, veri güvenliği, rekabet ve refah gibi sosyal boyutları da dikkate alınması gereken zorluklardan bazılarıdır (Fournel et al., 2017).

Sonuç ve Öneriler

Uygun bir sürdürülebilir üretim için hassas hayvancılık, hem yoğun hem de yaygın yetiştirme sistemlerinde hayvanların izlenmesine olanak tanıyan, uygulanabilirliği olan, yakın gelecekte önemli bir çözüm araçtır.

Hayvancılık sektöründeki kaynak tüketimi, yaygın çevresel etkileri göz önüne alındığında, hassas hayvancılık uygulamalarının hayvancılık işletmelerinin çevresel performansını daha sürdürülebilir bir geleceğe doğru iyileştirme konusunda büyük bir potansiyel sahip olduğu yönde ortak görüşler bulunmaktadır.

Çevresel, ekonomik ve sosyal açıdan olumlu etkiler yaratarak; hayvan, çiftçi, toplum ve tüketicileri de kapsayacak şekilde yaygınlaşabilmesi için, sürekli iyileştirmeler gerektiği ve hayvancılık üretiminin sürdürülebilirliğini artırmak için daha fazla disiplinlerarası araştırmaya ihtiyaç duyulduğu görüşüne ulaşılmaktadır.

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GIS-BASED ASSESSMENT OF POTENTIAL AND ACTUAL SOIL EROSION RISK USING THE CORINE MODEL: A CASE STUDY OF THE ERFELEK WATERSHED

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Abstract
This study aimed to spatially assess soil erosion risk in the Erfelek Watershed of Sinop Province, Türkiye, using the CORINE model integrated with Geographic Information Systems (GIS). Soil texture, soil depth, slope, and land cover were used as the main parameters of the erosion assessment. Soil-related layers were prepared using available soil data and information obtained from sampling points, while slope classes were derived from a digital elevation model with a 10 m spatial resolution. Land cover was evaluated based on CORINE 2018 land-cover classes. A common valid analysis area of 52,281.07 ha was used to ensure consistent comparison of the model outputs. Since spatially explicit stoniness data were unavailable for the study area, two alternative stoniness scenarios (S1 and S2) were developed to assess the influence of this parameter on erosion-risk estimates. Under S1, 49.12% of the analysis area was classified as low, 50.68% as moderate, and 0.20% as high potential erosion risk. Under S2, the proportion of low-risk areas decreased to 12.34%, whereas moderate- and high-risk areas increased to 57.96% and 29.71%, respectively. After incorporating the protective effect of land cover, actual erosion risk under S1 was classified as 82.94% low, 16.74% moderate, and 0.32% high. Under S2, the corresponding proportions were 46.04%, 46.10%, and 7.86%, respectively. The results demonstrate that alternative assumptions regarding stoniness can substantially alter the spatial distribution of erosion risk estimated by the CORINE model. Furthermore, land cover exhibited a pronounced protective effect, particularly by reducing the extent of high-risk areas. The scenario-based approach provides a practical framework for quantifying model uncertainty in regions where spatially detailed stoniness information is unavailable.
Keywords: CORINE, soil erosion, GIS, Erfelek Watershed

1. INTRODUCTION

Soil erosion is widely recognized as one of the major soil degradation processes threatening the functions of soil, one of the most important natural resources, within terrestrial ecosystems. Although soil erosion occurs under natural environmental conditions, it can be substantially accelerated by anthropogenic pressures such as inappropriate, unplanned, or non-purpose land use, intensive and poorly managed agricultural practices, land clearing and deforestation, and rangeland degradation caused by overgrazing. In particular, the removal of fertile topsoil by erosion can reduce soil health, quality, and productivity; impair soil functions such as water infiltration and storage and carbon and nutrient cycling; and adversely affect water resources through sediment transport. For these reasons, FAO identifies soil erosion as one of the major global threats to soil resources.

The occurrence and severity of soil erosion do not depend on a single parameter, but result from interactions among human activities, soil properties, topography, climate, and land cover/use. Soil structure, texture, depth, and surface roughness influence susceptibility to erosion, whereas topographic characteristics such as slope gradient, form, and length are particularly important in controlling runoff generation and erosion processes. Vegetation cover also determines the degree to which the soil surface

is exposed to or protected from the direct impact of rainfall and therefore influences the transition from potential erosion risk to the actual risk under existing land conditions. The CORINE erosion-risk approach similarly integrates these parameters to classify erosion risk spatially.

At the planning stage, assessment of erosion risk at watershed and regional scales requires the rapid and integrated evaluation of areas with different spatial characteristics. Geographic Information Systems (GIS) provide an effective framework for integrating soil, topographic, and land-cover data obtained from different sources within a common spatial structure and for visualizing areas with different levels of erosion risk.

One approach used for this purpose is the CORINE (Coordination of Information on the Environment) erosion model (1992), which was developed within the European Community to assess and map soil erosion risk and important land resources. The model provides a framework for generating comparable erosion-risk information, particularly over large areas. However, data availability was recognized as an important constraint during model development; consequently, CORINE is more appropriately regarded as a regional erosion-risk assessment approach than as a detailed process-based soil-loss model. For example, Everest and Özcan (2017) estimated erosion risk in the Dümrek Watershed using the CORINE method. They reported low, moderate, and high potential erosion risk over 66.80%, 22.25%, and 10.95% of the study area, respectively, whereas actual erosion risk was moderate over 38.67% and high over 61.33% of the area. They also identified slope and land cover as the factors exerting the strongest influence on erosion.

A key issue in applying the CORINE model at watershed or broader scales is the availability of all model inputs at sufficient spatial detail. Data availability has also been explicitly identified as an important limitation in studies concerning the development and application of the method. In particular, representing a spatially variable parameter such as surface stoniness by a single class when adequate data are unavailable may make model results dependent on the selected assumption. Accordingly, where the spatial distribution of stoniness cannot be determined, alternative conditions may be evaluated as separate scenarios to examine how uncertainty in this input is reflected in model outputs. This scenario-based treatment was adopted specifically in the present study. The standard CORINE method does not define an S1-S2 scenario procedure; therefore, this implementation constitutes a methodological distinction from conventional CORINE applications.

The aim of this study was to determine the spatial distribution of potential and actual soil erosion risk in the Erfelek Watershed, Sinop Province, Türkiye, using the CORINE model and GIS techniques. Soil texture, soil depth, slope, and land-cover characteristics were evaluated spatially. Because sufficiently detailed spatial data were not available to classify surface stoniness according to the 10% threshold used in the CORINE model, two alternative stoniness scenarios (S1 and S2) were developed. In addition to mapping potential and actual erosion risk across the watershed, the study therefore aimed to compare the influence of alternative assumptions regarding surface stoniness on model outputs.

2. MATERIALS AND METHODS

2.1. Study area

Sinop Province is located in northern Türkiye, in the central part of the Black Sea Region, between 41°12′-42°06′ N and 34°14′-35°26′ E. It is bordered by the Black Sea to the north, Kastamonu Province to the west, Çorum Province to the south, and Samsun Province to the southeast. The Erfelek Watershed, which constitutes the study area, is located in the northern part of Sinop Province and covers a total area of 52,281.07 ha (Figure 1). Sinop is influenced by the Black Sea climate and is characterized by humid and rainy conditions throughout the year. Owing to the strong maritime influence, seasonal temperature differences are relatively limited and coastal areas experience milder conditions. Precipitation is distributed throughout the year, with mean annual precipitation ranging from 679 to 1,077 mm. The mean annual temperature in central Sinop is approximately 14 °C, with mean temperatures of about 7 °C in winter and 20 °C in summer (Anonymous, 2026).

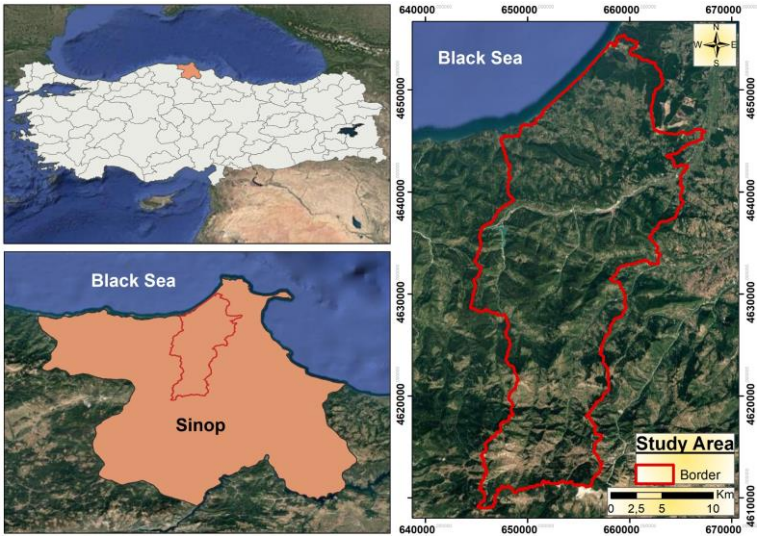


Figure 1. Location and spatial extent of the Erfelek Watershed within Sinop Province and Türkiye.

2.2. Preparation and Processing of Model Parameters

For preparation of the spatial data used in the CORINE model, the 52,281.07 ha Erfelek Watershed was adopted as the common study area. The model was implemented in a GIS environment to determine potential and actual soil erosion risk, using soil texture, soil depth, surface stoniness, slope, and land cover as the principal parameters (Figure 2).

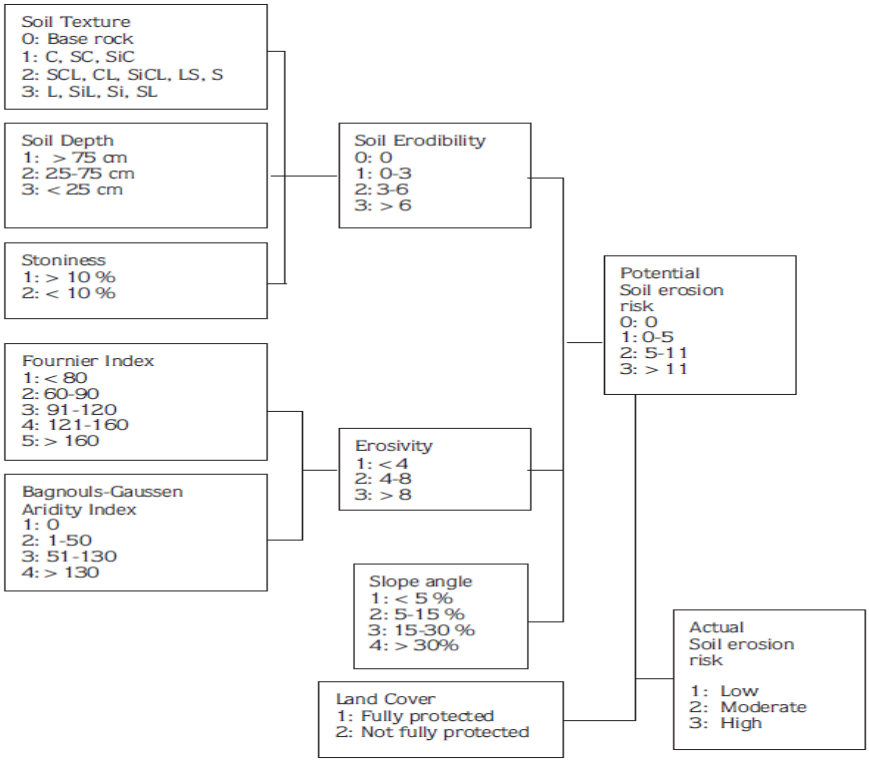


Figure 2. Flow diagram of the CORINE model.

Spatial layers of soil texture and soil depth were prepared using available soil data and information obtained from sampling points and were reclassified according to the CORINE methodology. Soil texture is an important property affecting aggregate stability and the detachment and transport of soil particles by rainfall and surface runoff. According to the CORINE classification approach, texture was evaluated in three classes: Class 1 represents soils with relatively low textural erodibility, Class 2 represents intermediate conditions, and Class 3 represents soils with relatively high textural erodibility (Figure ...). Soil depth, another property considered in determining soil erodibility, was also evaluated

in three classes: >75 cm, 25-75 cm, and <25 cm. Accordingly, soils deeper than 75 cm were assigned to Class 1, soils 25-75 cm deep to Class 2, and soils shallower than 25 cm to Class 3 (Figure ...).

Surface stoniness is another parameter used to determine soil erodibility in the CORINE model. However, because an adequate dataset describing the spatial distribution of surface stone cover was unavailable for the study area, two alternative scenarios, S1 and S2, were established for this parameter. Based on the 10% surface stone-cover threshold used in the CORINE approach, these scenarios represent two alternative model conditions rather than an observed spatial distribution of stoniness within the watershed. Thus, while all other model inputs were held constant, the effect of changing stoniness conditions on erosion-risk outputs was compared. Soil texture and depth classes were combined with the S1 and S2 stoniness scenarios to generate separate soil-erodibility layers for each scenario.

A 10 m spatial-resolution Digital Elevation Model (DEM) was used to represent the topographic factor. Slope values derived from the DEM as percentages were classified into four CORINE categories: <5%, 5-15%, 15-30%, and >30%. Combining soil erodibility and slope classes for each scenario produced the S1 and S2 potential erosion-risk layers (POT_S1 and POT_S2), which were subsequently classified as low, moderate, and high potential erosion risk.

In the final stage of the model, the protective effect of land cover against erosion was incorporated. CORINE Land Cover 2018 data were used, and land-cover classes were reclassified into two groups according to their soil-protection capacity: fully protected and not fully protected. Combining these land-cover protection classes with the S1 and S2 potential erosion-risk layers yielded actual erosion-risk layers (ACT_S1 and ACT_S2) for both scenarios. Actual erosion risk was also classified as low, moderate, or high. All spatial layers were harmonized to the same study-area boundary and spatial reference system before model analysis.

2.3.Soil texture

Soil texture influences both aggregate stability and the capacity of rainfall and surface runoff to detach and transport soil particles. In accordance with CORINE classification principles, soil texture information was converted into three relative erodibility classes. Class 1 represents soils with relatively low textural erodibility, Class 2 represents intermediate conditions, and Class 3 represents soils with relatively high textural erodibility. The resulting spatial distribution is presented in Figure 3. The map shows that Class 2 is widespread across the watershed, whereas Classes 1 and 3 occur in more spatially limited areas (Table 1).

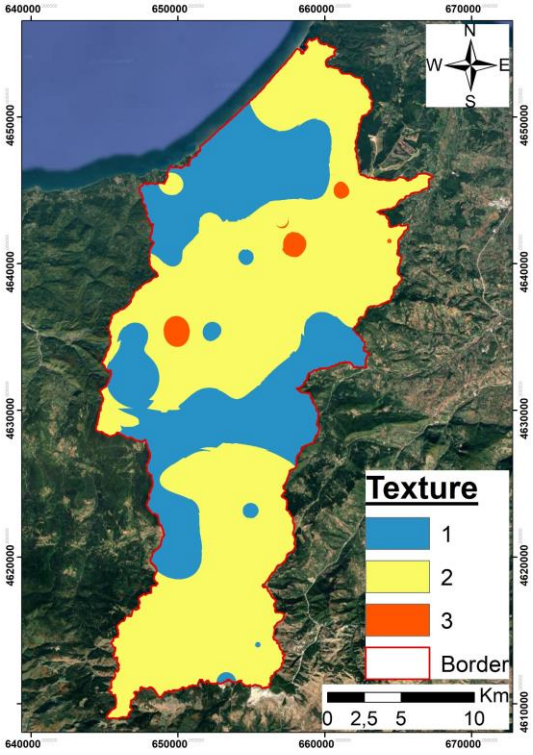


Figure 3. Spatial distribution of CORINE soil texture classes in the Erfelek Watershed.

Table 1. Areal and proportional distribution of CORINE soil texture classes.

Class	Texture	Area (ha)	Proportion (%)
1	Light-textured	16,918.87	32.36
2	Medium-textured	34,748.59	66.46
3	Heavy-textured	613.61	1.18
TOTAL		52,281.07	100.00

The distribution of soils in the Erfelek Watershed by texture class indicates that most of the study area consists of medium-textured soils (Class 2). This class covers 34,748.59 ha, corresponding to 66.46% of the total study area. Light-textured soils (Class 1) rank second, covering 16,918.87 ha (32.36%). Heavy-textured soils (Class 3) occupy only 613.61 ha (1.18%) and therefore have a very limited distribution within the watershed.

2.4. Soil depth

Soil depth affects erosion susceptibility because deep soil profiles generally have greater water-storage capacity, whereas shallow soils have a lower capacity to absorb and retain rainfall before surface runoff begins. Standard CORINE depth classes were adopted: soils deeper than 75 cm were assigned to Class 1, soils 25–75 cm deep to Class 2, and soils shallower than 25 cm to Class 3. The areal and proportional distribution of the soil depth classes is presented in Table 2, while their spatial distribution is shown in Figure 4. Moderately deep soils occupy a major part of the mapped watershed, whereas shallow soils occur in more localized areas.

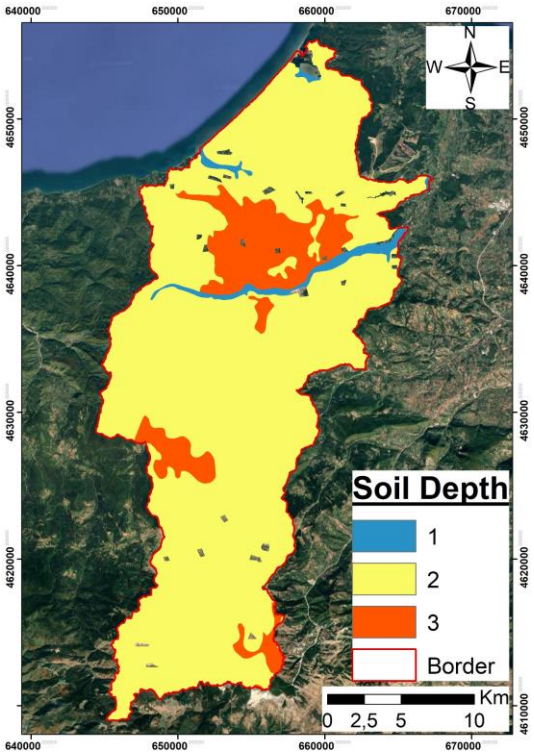


Figure 4. CORINE soil depth classes in the Erfelek Watershed.

Table 2. Areal and proportional distribution of CORINE soil depth classes in the Erfelek Watershed

Depth Class	Soil Depth	Erosion Susceptibility	Area (ha)	Proportion (%)
1	>75 cm	Low / less susceptible	1,047.66	2.00
2	25-75 cm	Moderately susceptible	45,037.18	86.15
3	<25 cm	Highly susceptible	6,196.23	11.85
TOTAL			52,281.07	100.00

The distribution of soils in the Erfelek Watershed by depth class shows that most of the study area consists of moderately deep soils (25-75 cm; Class 2). This class covers 45,037.18 ha, corresponding to 86.15% of the watershed. Shallow soils (<25 cm), which have greater susceptibility to erosion (Class 3), cover 6,196.23 ha (11.85%). In contrast, soils deeper than 75 cm, with lower erosion susceptibility

(Class 1), occupy only 1,047.66 ha (2.00%). This distribution demonstrates the clear dominance of moderately deep soils and the limited extent of deep soils with lower erosion susceptibility.

2.5. Surface stoniness scenarios

Surface stoniness is one of the components used to determine the CORINE soil-erodibility index. In the standard CORINE classification, areas with more than 10% surface stone cover are assigned a lower erodibility level because stones partially protect the soil surface from direct raindrop impact, whereas areas with less than 10% stone cover are considered to have limited protection. However, a sufficiently reliable dataset for mapping the spatial distribution of surface stoniness and classifying it according to the 10% threshold was unavailable for the study area. Therefore, two alternative scenarios (S1 and S2) were developed to evaluate the influence of stoniness conditions on CORINE model outputs. One scenario represents a surface stone-cover condition of >10%, while the other represents <10%; all other model parameters were held constant and potential erosion risk was calculated separately for each condition. In this way, the absence of detailed spatial stoniness data was addressed by evaluating model behavior under alternative conditions rather than by adopting a single assumption.

2.6. Slope classification

Slope was derived from a 10 m spatial-resolution Digital Elevation Model (DEM) and classified into four categories according to the CORINE methodology: <5%, 5-15%, 15-30%, and >30%. The areal and proportional distributions of the slope classes are presented in Table 3, and the slope map is shown in Figure 5.

Table 3. Areal and proportional distribution of slope classes.

Slope Class	Slope (%)	Area (ha)	Proportion (%)
1	0-5	3,002.28	5.74
2	5-15	9,932.20	19.00
3	15-30	17,387.87	33.26
4	>30	21,958.72	42.00
TOTAL		52,281.07	100.00

The distribution of slope classes in the Erfelek Watershed indicates that a substantial proportion of the study area consists of steep terrain. Areas with slopes >30% cover 21,958.72 ha (42.00%), while slopes of 15-30% account for 17,387.87 ha (33.26%). In comparison, slopes of 5-15% account for 19.00% of the watershed, and relatively flat areas with slopes of 0-5% account for only 5.74%. Thus, approximately 75.26% of the study area has slopes exceeding 15%, indicating a generally rugged topography. Because slope is a fundamental factor in determining potential erosion risk in the CORINE model, the extensive occurrence of steep terrain represents an important topographic control on the spatial distribution of erosion risk.

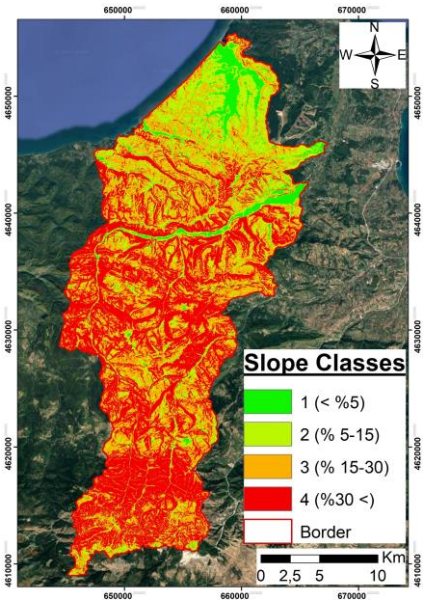


Figure 5. Slope classes of the study area.

The 15-30% and >30% slope classes are concentrated over broad, fragmented areas, particularly in the central and southern parts of the watershed. In contrast, the <5% and 5-15% slope classes are more evident in the northern part of the watershed and along valley floors.

2.7. Land-cover protection

CORINE 2018 land-cover data were divided into two categories according to their capacity to protect the soil surface. Areas with relatively continuous and protective cover were assigned to the fully protected class, whereas land-cover categories providing less protection were assigned to the not fully protected class.

This classification forms the principal distinction between potential and actual erosion risk. Potential risk reflects the inherent susceptibility before current land-cover protection is considered, whereas actual risk represents the erosion-risk class after existing land-cover conditions are incorporated into the model. The areal and proportional distribution of the land-cover protection classes is presented in Table 4, while their spatial distribution across the study area is shown in Figure 6.

Table 4. Areal and proportional distribution of land-cover protection classes.

Land-Cover Class	Protection Status	Area (ha)	Proportion (%)
1	Fully protected	31,535.52	60.32
2	Not fully protected	20,745.55	39.68
TOTAL		52,281.07	100.00

The distribution of land cover according to protection status shows that 31,535.52 ha (60.32%) of the Erfelek Watershed is classified as fully protected, whereas 20,745.55 ha (39.68%) is classified as not fully protected. The spatial distribution of the land-cover protection classes is presented in Figure 5.

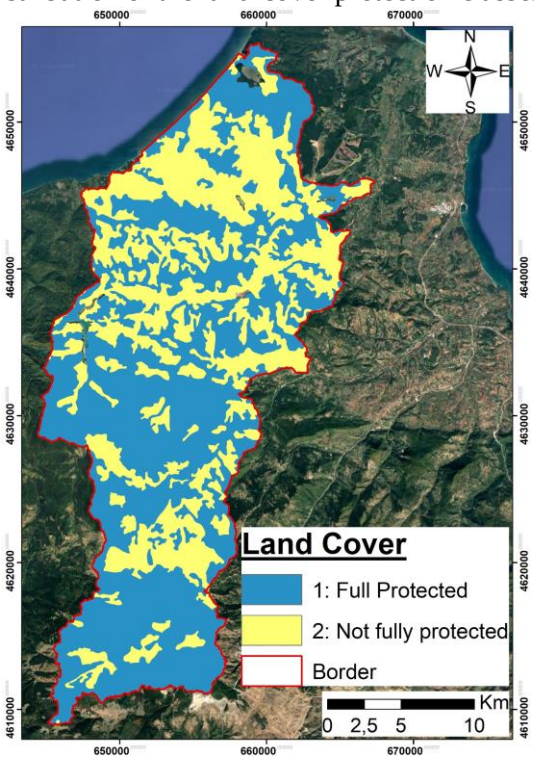


Figure 6. Spatial distribution of land-cover protection classes according to the CORINE model.

Of the study area, 60.32% (31,535.52 ha) is fully protected and 39.68% (20,745.55 ha) is not fully protected. Fully protected areas occupy broader areas particularly in the southern part of the watershed, whereas not fully protected areas show a more widespread and fragmented distribution in the northern and central parts. This difference in land cover influences the conversion of potential erosion risk into actual erosion risk in the CORINE model.

2.8. Mapping potential and actual erosion risk

Potential erosion risk was obtained by spatially integrating the soil-erodibility and topographic components of the CORINE framework.

The resulting potential erosion values were classified into low, moderate, and high risk categories. The procedure was performed separately for S1 and S2, producing two potential erosion-risk maps.
Actual erosion risk was subsequently assessed by combining the potential erosion-risk layer with the CORINE land-cover protection layer. This step was also performed separately for the two stoniness scenarios. Consequently, four principal outputs were obtained: potential erosion risk under S1, potential erosion risk under S2, actual erosion risk under S1, and actual erosion risk under S2.
The area occupied by each risk class was calculated in hectares and as a percentage of the common valid analysis area.

3. RESULTS AND DISCUSSION

3.1. Spatial characteristics of model inputs

The spatial input layers reveal substantial environmental heterogeneity across the Erfelek Watershed. The intermediate CORINE texture class is dominant, although extensive areas of the lower-erodibility class and smaller areas of the higher-erodibility class are also present. Soil depth shows a similarly heterogeneous distribution: moderately deep soils cover most of the watershed, while shallow soils are concentrated in specific areas. Dengiz et al. (2019) likewise demonstrated that land cover and soil properties such as texture and depth jointly shape the spatial variability of soil characteristics in a sub-humid watershed.
Topographic variability is particularly pronounced. The slope map shows broad areas of relatively gentle terrain in the northern part of the watershed, while steep and very steep slopes become increasingly prevalent toward the central and southern parts. The spatial pattern of the erosion-risk maps closely follows this topographic pattern, particularly under the less protective stoniness assumption.
This observation is consistent with previous CORINE applications in which topography was identified as an important control on erosion susceptibility. Khallouf et al. (2021) identified slope and land use/land cover as major determinants of spatial erosion risk, while Akbari et al. (2022) reported that potential risk is particularly sensitive to soil texture, slope, and soil depth. The extensive distribution of steep terrain in the Erfelek Watershed therefore represents an important source of potential erosion susceptibility.
A previous study in the Erfelek Dam Creek Watershed also reported that soil-erodibility indices varied substantially with both land-use type and parent material (Yilmaz et al., 2008). This finding supports the spatially explicit approach used in the present study rather than representing the watershed by a single generalized soil condition.

3.2. Potential soil erosion risk

Potential erosion-risk distributions differed markedly between the two stoniness scenarios. Under S1, 25,680.13 ha, corresponding to 49.12% of the common analysis area, was classified as low potential erosion risk. Moderate risk covered 26,494.47 ha (50.68%), whereas high risk was limited to only 106.47 ha (0.20%). Thus, approximately half of the watershed was classified as low risk and the other half as moderate risk, while high potential risk remained spatially very limited. The spatial distribution of potential soil erosion risk under the S1 scenario is shown in Figure 7.

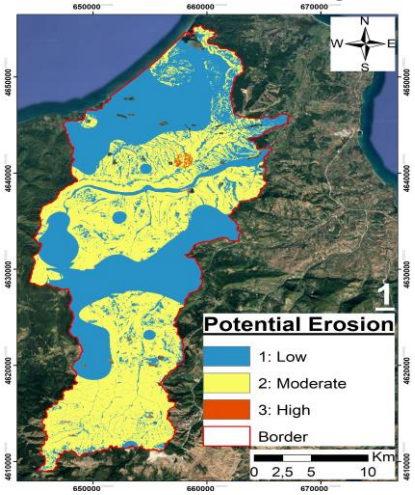


Figure 7. Distribution of potential soil erosion risk under Stoniness Scenario 1 (S1).

Under S2, the distribution changed substantially. The low-risk area decreased to 6,450.17 ha (12.34%), while the moderate-risk class increased to 30,299.78 ha (57.96%). The most notable change was the expansion of the high potential erosion-risk class to 15,531.12 ha, corresponding to 29.71% of the analysis area. The spatial distribution of potential soil erosion risk under the S2 scenario is shown in Figure 8. The areal and proportional distributions of potential and actual soil erosion-risk classes under the S1 and S2 scenarios are presented in Table 5.

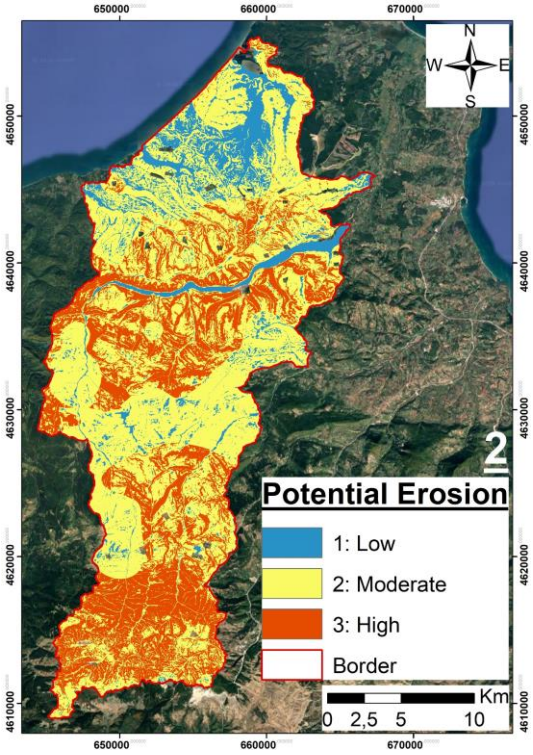


Figure 8. Distribution of potential soil erosion risk under Stoniness Scenario 2 (S2).

Table 5. Distribution of potential and actual soil erosion-risk classes.

Erosion Type	Scenario	Risk Class	Area (ha)	Proportion (%)
Potential	S1	Low	25,680.13	49.12
Potential	S1	Moderate	26,494.47	50.68
Potential	S1	High	106.47	0.20
Potential	S2	Low	6,450.17	12.34
Potential	S2	Moderate	30,299.78	57.96
Potential	S2	High	15,531.12	29.71
Actual	S1	Low	43,362.36	82.94
Actual	S1	Moderate	8,753.59	16.74
Actual	S1	High	165.12	0.32
Actual	S2	Low	24,068.05	46.04
Actual	S2	Moderate	24,103.07	46.10
Actual	S2	High	4,109.95	7.86

The transition from S1 to S2 reduced the proportion of low potential-risk areas by 36.78 percentage points and increased the high-risk proportion by approximately 29.50 percentage points. Accordingly, the area classified as high potential risk under S2 was substantially larger than under S1.

These results show that surface stoniness is an influential input in this application of the CORINE model. Because stoniness forms part of the multiplicative soil-erodibility component, a change in the assigned class propagates through the subsequent risk classification and may shift extensive areas from lower to higher risk categories.

This finding has an important methodological implication. If spatially explicit stoniness information were replaced by a single assumed value, the resulting erosion-risk map could appear definitive even

though it would represent only one of several plausible outcomes. The scenario approach makes this sensitivity visible and quantitatively comparable.

3.3. Actual soil erosion risk under S1

When land-cover protection was incorporated into the S1 potential-risk assessment, the proportion of low actual erosion risk increased markedly to 82.94%, corresponding to 43,362.36 ha. Moderate actual risk covered 8,753.59 ha (16.74%), while high actual risk was limited to 165.12 ha (0.32%). The spatial distribution of actual soil erosion risk under the S1 scenario is shown in Figure 9.

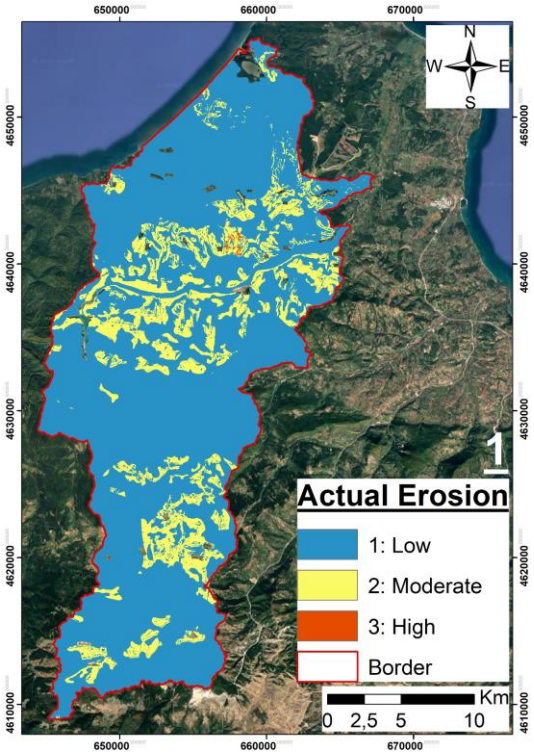


Figure 9. Distribution of actual soil erosion risk under Stoniness Scenario 1 (S1).

The most pronounced change relative to potential risk was the transition of extensive areas from the moderate category to the low actual-risk category. Low risk increased by approximately 33.82 percentage points, while moderate risk decreased by approximately 33.93 percentage points.

Although the high-risk proportion changed only slightly and remained below 0.4%, the overall spatial distribution clearly indicates a strong mitigating effect of existing land-cover conditions under S1. This distinction between potential and actual risk is a key advantage of the CORINE framework because it separates the inherent susceptibility of the landscape from the risk expressed under current vegetation and land-use conditions.

Similar effects of vegetation and land cover have been reported in previous CORINE studies. Aydın and Tecimen (2010) showed that land-use conditions altered the spatial distribution of actual erosion risk in the Elmalı Dam Watershed, while Yuksel et al. (2008) demonstrated the value of incorporating remotely sensed land-cover information into CORINE-based erosion mapping. These findings are also consistent with the general understanding that continuous vegetation cover reduces soil exposure to raindrop impact and surface runoff.

3.4. Actual soil erosion risk under S2

The protective effect of land cover was even more evident under S2. Under this less protective stoniness condition, the high potential-risk class covered 29.71% of the watershed. After land cover was incorporated into the model, the area of high actual risk decreased to 4,109.95 ha (7.86%). At the same time, low actual erosion risk increased from 12.34% at the potential-risk stage to 46.04%, while moderate actual risk accounted for 46.10% of the analysis area. The spatial distribution of actual soil erosion risk under the S2 scenario is shown in Figure 10.

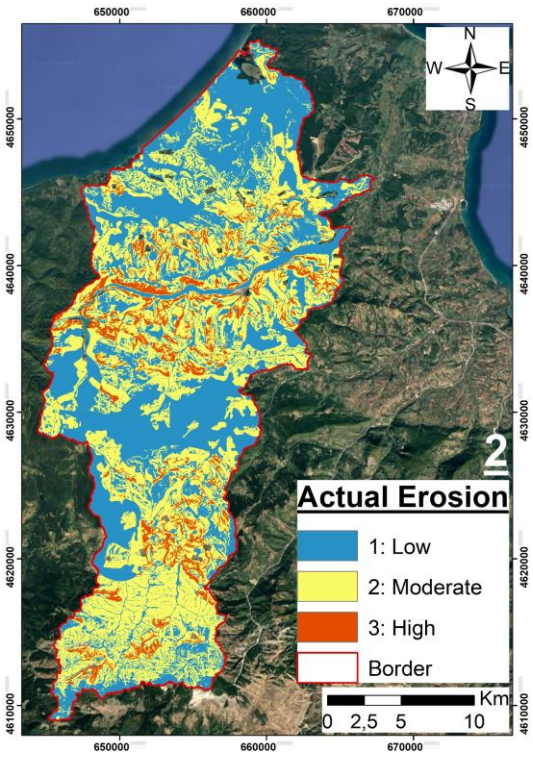


Figure 10. Distribution of actual soil erosion risk under Stoniness Scenario 2 (S2).

Thus, under S2, the high-risk proportion decreased by approximately 21.85 percentage points from potential to actual risk. Relative to its potential extent, the area assigned to the high-risk class declined by approximately three quarters after land-cover conditions were incorporated.

The maps show that most areas remaining in the moderate or high actual-risk classes coincide with steep terrain and less protective land cover. In contrast, extensive areas with high inherent susceptibility shift to lower actual-risk categories where vegetation provides stronger surface protection.

This behavior is consistent with the conceptual structure of the CORINE model and findings from other regions. Tayebi et al. (2017) emphasized that actual erosion risk is jointly controlled by potential erosion susceptibility and vegetation cover, while Akbari et al. (2022) demonstrated that vegetation plays an important role in determining actual risk even where inherent susceptibility related to soil and topography remains high.

3.5. Influence of stoniness scenarios

Comparison of the two scenarios developed for the stoniness parameter showed that alternative surface-stoniness conditions exerted a strong influence on both potential and actual erosion-risk maps.

For potential risk, the proportion of the watershed classified as high risk was only 0.20% under S1 but reached 29.71% under S2. Moderate potential risk ranged from 50.68% to 57.96%, while low potential risk ranged from 12.34% to 49.12%. The scenario effect remained evident after land cover was incorporated: high actual erosion risk ranged from 0.32% to 7.86%, moderate actual risk from 16.74% to 46.10%, and low actual risk from 46.04% to 82.94%. These ranges should not be interpreted as conventional statistical confidence intervals; rather, they represent the sensitivity of the categorical CORINE output to two alternative assumptions for an input parameter for which detailed spatial data were unavailable. In this sense, the analysis provides a practical range of possible erosion-risk classifications under the two modeled conditions.

Another important finding is that land cover moderated part of the difference associated with high-risk classification. The difference in high potential risk between S1 and S2 was approximately 29.5 percentage points, whereas the corresponding difference between high actual-risk classes was approximately 7.5 percentage points. Thus, existing surface-cover protection substantially limited the extent to which differences in the stoniness condition were reflected in the highest actual-risk category.

The differences between the two scenarios also indicate the value of obtaining more spatially detailed stoniness information in future CORINE applications. Field observations or remote-sensing-supported

surveys of surface stoniness could allow the scenario layers to be refined into a spatially differentiated stoniness layer and thereby further strengthen erosion-risk assessment.

3.6. Implications for watershed management

Erosion-risk maps are useful not because they directly quantify annual soil loss, but because they qualitatively identify where combinations of climate, soil properties, topography, and land-cover conditions create relatively greater vulnerability. They can therefore provide rapid spatial information to support decision makers and planners in prioritizing areas for further assessment and management.

Under the more conservative S2 assumption used in this CORINE application, areas of high potential risk are concentrated particularly on steep terrain in the central and southern parts of the watershed. Although land-cover protection substantially reduces the extent of high actual erosion risk, some spatially coherent risk zones remain. These areas may be appropriate targets for more detailed field investigations before erosion-control measures are prioritized. The results also emphasize the importance of maintaining existing protective land cover. Areas currently showing low actual risk may nevertheless have moderate or high inherent susceptibility; removal or degradation of protective vegetation could expose the underlying potential erosion risk. Therefore, comparison of potential and actual risk maps provides more management-relevant information than a single erosion-risk map alone.

4. CONCLUSIONS AND RECOMMENDATIONS

In this study, potential and actual soil erosion risk in the Erfelek Watershed was spatially assessed using the CORINE model and GIS techniques. Soil properties, topography, and land-cover data were integrated within the model, while surface stoniness was represented through two alternative scenarios under the available data conditions. This approach enabled the effects of different surface conditions on erosion-risk classes to be evaluated comparatively.

The topographic characteristics of the watershed indicate conditions that are important for erosion assessment. Approximately 75.26% of the study area has slopes greater than 15%, demonstrating the extensive occurrence of steep and very steep terrain. Nevertheless, the spatial distribution of erosion risk cannot be explained by slope alone; soil properties, surface conditions, and land cover need to be considered together.

Scenario analysis showed that potential erosion risk was concentrated mainly in the low and moderate classes under S1, whereas moderate- and high-risk areas became more prominent under S2. High potential erosion risk accounted for 0.20% under S1 and 29.71% under S2. After the protective effect of land cover was incorporated, high actual erosion risk accounted for 0.32% under S1 and 7.86% under S2. These differences demonstrate that alternative surface conditions can influence the spatial distribution of erosion risk estimated by the CORINE model. The scenario-based approach therefore enabled the model to be evaluated under two plausible conditions where detailed spatial information on surface stoniness was unavailable.

Incorporating land cover produced marked changes in the distribution of potential and actual erosion risk. The finding that 60.32% of the watershed belongs to the fully protected land-cover class highlights the importance of surface protection, particularly in erosion-susceptible areas. This result indicates that maintaining existing vegetation and land cover is an important component of erosion-risk reduction and sustainable watershed management.

Overall, integrating the CORINE model with GIS enabled erosion risk in the Erfelek Watershed to be mapped spatially and the effects of alternative surface conditions on model outputs to be compared. The use of two surface-stoniness scenarios maintained the applicability of the model under the available data conditions while allowing the results to be assessed under different plausible conditions. The resulting risk maps can provide useful spatial information for identifying erosion-susceptible areas, prioritizing soil and water conservation measures, protecting land cover, and planning sustainable land management at the watershed scale.

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KURAKLIK STRESİNİN TAHILLARDA TOHUMLUK KALİTESİ ÜZERİNE ETKİLERİ

EFFECTS OF DROUGHT STRESS ON SEED QUALITY IN CEREAL CROPS

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ÖZET
Kuraklık, tahıl üretimini sınırlandıran önemli abiyotik stres faktörlerinden biri olup etkileri yalnızca tane verimindeki azalmalarla sınırlı değildir. Tohumluk üretimi sırasında meydana gelen su noksanlığı; döllenme, embriyo ve endosperm gelişimi, asimilatların gelişmekte olan tohumlara taşınması, depo maddelerinin birikimi ve olgunlaşma süreçlerini etkileyerek elde edilen tohumluğun fiziksel ve fizyolojik kalitesinde değişikliklere neden olabilmektedir. Özellikle çiçeklenme, tohum gelişimi ve tane doldurma dönemlerinde meydana gelen kuraklık, tohum iriliği, ağırlığı ve dolgunluğu gibi fiziksel kalite özelliklerini olumsuz etkileyebilmektedir. Bunun yanında, çimlenme dönemindeki düşük su potansiyeli tohumun su alımını ve metabolik aktivitesini sınırlandırarak depo maddelerinin mobilizasyonunu, çimlenmeyi ve erken fide gelişimini baskılayabilmektedir. Kuraklık koşullarında çimlenme oranı ve hızında azalma, çimlenmenin gecikmesi, vigor kaybı ile kök ve sürgün gelişiminde gerileme görülebilmektedir. Tohumluk kalitesinde meydana gelen bu değişimler, ekim sonrasında homojen çıkışın sağlanmasını ve bitkilerin erken dönemde başarılı bir şekilde gelişmesini de etkileyebilmektedir. Bu nedenle kuraklığın tohumluk üzerindeki etkilerinin yalnızca hasat edilen tohumların fiziksel özellikleri üzerinden değerlendirilmesi yeterli değildir. Bununla birlikte, bu etkilerin büyüklüğü tahıl türü, genotip, stresin şiddeti ve süresi ile meydana geldiği gelişme dönemine bağlı olarak önemli ölçüde değişmektedir. Buğday, arpa, mısır, çeltik ve sorgumda yapılan çalışmalar, kuraklığın tohumluk ve erken gelişim özellikleri üzerinde farklı etkiler oluşturduğunu ve genotipler arasında belirgin varyasyon bulunduğunu ortaya koymaktadır. Tohumluk üretimi sırasında meydana gelen kuraklığın elde edilen tohumların sonraki çimlenme ve fide performansına yansıması, sürdürülebilir tahıl üretimi açısından ayrıca önem taşımaktadır. Bu nedenle kuraklık toleransının değerlendirilmesinde yalnızca tane veriminin değil; tohum ağırlığı, çimlenme, vigor, tarla çıkışı ve erken fide gelişimi gibi özelliklerin birlikte ele alınması gerekmektedir. Sonuç olarak, değişen iklim koşullarında tahıllarda yüksek tane veriminin yanı sıra kuraklık koşullarında fiziksel ve fizyolojik kalitesini koruyabilen kaliteli tohumluk üretiminin sürdürülmesi de önem taşımaktadır.
Anahtar kelimeler: Kuraklık, tahıllar, tohumluk kalitesi, çimlenme.

ABSTRACT
Drought is one of the major abiotic stress factors limiting cereal production, and its effects are not restricted to reductions in grain yield. Water deficit during seed production may affect fertilization, embryo and endosperm development, assimilate translocation to developing seeds, reserve accumulation, and maturation, thereby causing changes in the physical and physiological quality of the resulting seed. Drought occurring particularly during flowering, seed development, and grain filling may adversely affect physical quality traits such as seed size, weight, and plumpness. In addition, low water potential during germination may restrict seed water uptake and metabolic activity, thereby limiting reserve mobilization, germination, and early seedling development. Under drought conditions, reductions in germination percentage and rate, delayed germination, loss of vigor, and restricted root and shoot growth may occur. These changes in seed quality may also affect uniform emergence and successful early plant development after sowing. Therefore, evaluating the effects of drought on seeds solely on the basis of the physical characteristics of harvested seed is insufficient. Nevertheless, the magnitude of these effects varies considerably depending on cereal species, genotype, stress intensity and duration, and the developmental stage at which the stress occurs. Studies conducted on wheat,

barley, maize, rice, and sorghum have demonstrated that drought has different effects on seed quality and early developmental traits and that considerable variation exists among genotypes. The effects of drought occurring during seed production on the subsequent germination and seedling performance of the resulting seed are also of particular importance for sustainable cereal production. Therefore, the assessment of drought tolerance should consider not only grain yield but also seed weight, germination, vigor, field emergence, and early seedling development. In conclusion, under changing climatic conditions, maintaining the production of high-quality seed capable of preserving its physical and physiological quality under drought conditions is important in addition to sustaining high grain yield in cereals.
Keywords: Drought, cereals, seed quality, germination.

GİRİŞ

Tahıllar, diğer kültür bitkisi gruplarına kıyasla dünya genelinde geniş alanlarda yetiştirilmeleri ve insan beslenmesinde önemli bir enerji kaynağı olmaları sebebiyle temel gıda kaynakları arasında önemli bir yere sahiptir (Sarwarve ark., 2013). Bununla birlikte, tahıl üretimi çevresel stres faktörlerinden önemli ölçüde etkilenmektedir. Küresel iklim değişikliğinin kültür bitkilerinin verim düzeyleri üzerinde önemli etkiler oluşturabileceği ve gıda güvenliğinin sağlanabilmesi açısından ele alınması gereken temel sorunlardan biri olduğu kabul edilmektedir (Tripathi ve ark., 2016; Howden ve ark., 2007). Özellikle iklim değişikliğine bağlı olarak yağış rejimlerindeki düzensizlikler, sıcaklık artışları ve kurak dönemlerin sıklık ve şiddetindeki artış, tarımsal üretimin sürdürülebilirliği açısından önemli bir tehdit oluşturmaktadır. Kuraklık; bitkilerde su ilişkilerini, fotosentezi, karbon metabolizmasını, besin elementi alımını, hormonal dengeyi ve kaynak-havuz ilişkilerini etkileyerek büyüme ve gelişmeyi sınırlandırmaktadır (Bapela ve ark., 2022; Pandey ve ark., 2022; Wu ve Yang, 2024).

Kuraklık stresi, bitkilerin büyüme ve gelişiminin birçok yönünü olumsuz etkileyen önemli bir sınırlayıcı faktör olarak kabul edilmektedir (Alghbari ve Ihsan, 2018; Kapoor ve ark., 2020). Tohum çimlenmesi ve sağlığı, koleoptil uzunluğu ve yaprak alanı, bitkinin gelişimi açısından büyük önem taşımaktadır. Tohum çimlenmesi, kuraklık stresine karşı duyarlılık gösteren büyüme ve gelişme süreçlerinin başında gelmektedir (Kapoor ve ark., 2020). Erken vejetatif dönemde su noksanlığına maruz kalan bitkilerde, çimlenme oranındaki azalmanın yanı sıra yapraklarda solgunluk da belirgin bir stres belirtisi olarak ortaya çıkmaktadır. Su yetersizliği ayrıca sürgün uzunluğu ve hipokotil yaş ağırlığında azalmaya yol açarak bitki büyümesini olumsuz etkilemektedir (Abobatta, 2019). Bunun yanında, toprağın kurumasıyla birlikte bitki tarafından besin elementlerinin alımının kısıtlanması, tomurcuk ve çiçek oluşumunun sekteye uğramasına neden olabilmektedir (Abobatta, 2019; Kapoor ve ark., 2020).

Buğdayda başaklanma sonrasında meydana gelen kuraklığın tane dolum hızı üzerindeki etkisinin sınırlı olduğu, ancak tane dolum süresini kısalttığı ve bunun sonucunda olgunluk dönemindeki tane kuru ağırlığını azalttığı bildirilmiştir (Wardlaw ve Willenbrink, 2000). Arpada ise kuraklık stresi; kardeş sayısı, başak sayısı, bitki başına tane sayısı ve bireysel tane ağırlığında azalmaya neden olarak tane verimini düşürmektedir. Çiçeklenme sonrası dönemde meydana gelen kuraklık stresinin, stresin şiddetinden bağımsız olarak tane verimi üzerinde olumsuz etkiler oluşturduğu bildirilmiştir (Samarah, 2005; Alghbari ve Ihsan, 2018).

KURAKLIK VE TOHUM GELİŞİMİ

Yetersiz su mevcudiyeti, bitki bünyesinde kısa sürede su noksanlığının ortaya çıkmasına neden olmaktadır. Buna bağlı olarak gelişen dehidrasyon; bitkinin metabolizmasını, büyüme ve gelişmesini ve morfolojik yapısını önemli ölçüde etkilemektedir. Su noksanlığı koşullarında fizyolojik süreçlerde meydana gelen kapsamlı değişimler, büyümenin yavaşlamasına veya tamamen durmasına yol açarak verim kararlılığını tehdit etmektedir (Anjum ve ark., 2011). Tarla koşullarında kuraklığa bağlı verim kayıpları genellikle %30–90 arasında değişmekte ve bu kayıpların düzeyi bitki türlerine göre önemli farklılıklar göstermektedir (Hussain ve ark., 2019).

Birçok kültür bitkisinde tohum ve meyveler, hasat edilen temel veya tek ekonomik ürünü oluşturmaktadır (Şekil 3). Bu nedenle tozlanma, tohum tutumu ve meyve gelişimi, ürün veriminin oluşumunda belirleyici rol oynayan kritik gelişme süreçleridir. Hayvanlar aracılığıyla tozlanan çiçeklerde tozlanma başarısı, polen miktarı ve nektar mevcudiyetine bağlı olup, sera koşullarında yürütülen bir çalışmada her iki özelliğin de kuraklık stresi altında azaldığı belirlenmiştir (Waser ve Price, 2016). Tozlanmayı izleyen süreçte polen tüpü gelişiminin de kuraklık koşullarında baskılandığı ve bu

durumun karbonhidrat mobilizasyonundaki azalmayla ilişkili olabileceği bildirilmiştir (Hu ve ark., 2019). Kuraklık stresi altında gelişmekte olan taneler arasında sınırlı karbon kaynakları için meydana gelen rekabet, tohumların gelişimini tamamlayamamasına neden olabilmekte; kontrollü tozlanma uygulamalarının ise bu kayıpları azaltabildiği bildirilmektedir (Shen ve ark., 2020). Bunun yanı sıra, tozlanma ve tohum tutumunun başarısız olması veya floem yoluyla taşınan asimilatlar için oluşan rekabet, çiçek dökülmesine neden olabilmektedir (Patrick ve Stoddard, 2010).

Başarılı bir tozlanma ve tohum tutumunun ardından, tohum dolumu ve meyve gelişiminin sürdürülebilmesi asimilatların gelişmekte olan organlara etkin biçimde taşınmasına bağlıdır. Kuraklık koşullarında fotosentezin baskılanmasına bağlı olarak asimilat mevcudiyetinin azalması ve asimilatların bitki organları arasındaki dağılımının değişmesi, bitkinin kuraklık stresine karşı büyüme tepkisinin belirlenmesinde önemli rol oynamaktadır. Kuraklık altında asimilat dağılımının yeniden düzenlenmesine, karbonhidrat metabolizması ve taşınımında görev alan genlerin ekspresyonundaki değişimler eşlik etmektedir (Dietz ve ark., 2021).

KURAKLIĞIN FİZİKSEL VE FİZYOLOJİK TOHUMLUK KALİTESİNE ETKİLERİ

Kuraklık nedeniyle fotosentez ve asimilat taşınımının sınırlandırılması, özellikle tane doldurma döneminde kuru madde birikiminin azalmasına yol açabilmektedir. Bunun sonucunda tohum iriliği, tane ağırlığı ve dolgunluğu azalabilmekte; cılız veya buruşuk tohumların oranı artabilmektedir (Barnabás ve ark., 2008; Sehgal ve ark., 2018; Sallam ve ark., 2019). Gelişmekte olan tohumdaki rezerv birikiminin değişmesi, sonraki çimlenme ve fide gelişimi için kullanılabilecek kaynak miktarını da etkileyebilir.

Kuraklık, tohumluğun fizyolojik kalitesini de doğrudan veya dolaylı olarak etkileyebilmektedir. Düşük su potansiyeli tohumun su alımını sınırlandırarak imbibisyonu ve metabolik aktivasyonu geciktirmekte; depo maddelerinin mobilizasyonu ve embriyonik eksenin gelişimini baskılayabilmektedir. Bunun sonucunda çimlenme yüzdesi ve hızı, vigor, normal fide oranı, kök ve sürgün gelişimi azalabilmektedir (Soltani ve ark., 2006; Finch-Savage ve Bassel, 2016; Thabet ve ark., 2020; Ahmed ve ark., 2025).

Buğdayda artan ozmotik stres altında çimlenme, kök ve sürgün uzunluğu, fide biyokütlesi ve vigor indeksinin azaldığı bildirilmiştir (Ahmed ve ark., 2025). Benzer şekilde mısırda kuraklık çimlenme oranı ve enerjisi ile radikula ve koleoptil gelişimini baskılamıştır (Du ve ark., 2025). Sorgumda ise çimlenme ve fide dönemindeki kuraklık toleransı bakımından genotipler arasında geniş varyasyon bulunduğu belirlenmiştir (Wang ve ark., 2025).

TAHIL TÜRLERİNİN KURAKLIK STRESİNE TEPKİLERİ

Kuraklığa verilen tepki türler arasında farklılık gösterdiği gibi aynı tür içerisindeki genotipler arasında da önemli varyasyon göstermektedir. Bu nedenle kuraklığın tohumluk kalitesi üzerindeki etkileri değerlendirilirken tür × genotip × stres şiddeti × stres süresi × gelişme dönemi etkileşimi dikkate alınmalıdır (Sallam ve ark., 2019; Prasad ve ark., 2021; Seleiman ve ark., 2021).

Tablo 1. Tahıl Türlerinin Tohumluk ve Erken Gelişim Döneminde Kuraklığa Tepkileri

Tahıl	Kuraklığın Uygulandığı Dönem	Değerlendirilen Özellikler	Başlıca Etkiler	Kaynak
Buğday (*Triticum aestivum* L.)	Çimlenme ve fide dönemi	Çimlenme, vigor, kök-sürgün gelişimi, biyokütle	Çimlenme, vigorda ve kök-sürgün gelişimi azalma; genotipik farklılık	Ahmed ve ark. (2025)
Arpa (*Hordeum* spp.	Tohum gelişimi dönemi	Tane verimi, irilik, vigor, metabolik özellikler	Tane veriminde azalma; metabolik değişimler; genotipik farklılık	Nagel ve ark., (2022)
Mısır (*Zea mays* L.)	Çimlenme ve fide dönemi	Çimlenme, radikula-koleoptil gelişimi, biyokütle	Çimlenme, radikula-koleoptil gelişimi ve biyokütlede azalma	Du ve ark. (2025)
Çeltik (*Oryza sativa* L.)	Çiçeklenme ve tohum oluşum dönemi	Çimlenme, tane kalitesi, depolama ömrü	Erken kuraklıkta kalite kaybı, çimlenme ve	Rahman ve Ellis (2019)

			depolama ömründe azalma	
Sorgum (Sorghum bicolor L.)	Çimlenme ve fide dönemi	Çimlenme ve vigor	Çimlenme ve vigor özelliklerinde değişim; belirgin genotipik varyasyon	Wang ve ark. (2025)

Kuraklığın tohumluk ve erken gelişim özellikleri üzerindeki etkileri, stresin meydana geldiği gelişme dönemi ve genotipe bağlı olarak değişmektedir (Tablo 1). Arpa ve çeltikte yapılan çalışmalarda, tohum üretimi sırasında meydana gelen kuraklık stresinin elde edilen tohumların özelliklerini etkilediği belirlenmiştir (Rahman ve Ellis, 2019; Nagel ve ark., 2022). Buna karşılık, buğday, mısır ve sorgumda yapılan çalışmalarda tohumların kuraklık koşullarındaki çimlenme ve erken fide gelişimi bakımından belirgin genotipik farklılıklar gösterdiği ortaya konulmuştur (Ahmed ve ark., 2025; Du ve ark., 2025; Wang ve ark., 2025).

Bu sonuçlar, kuraklık toleransının yalnızca tane verimi veya tek bir çimlenme özelliği üzerinden değerlendirilmemesi gerektiğini göstermektedir. Tohumluk üretimi sırasında maruz kalınan stres ile elde edilen tohumların sonraki performansı arasındaki ilişkinin ortaya konulması, sürdürülebilir tohumluk üretimi açısından önemli bir araştırma alanıdır.

SONUÇ

Kuraklık, tahıllarda yalnızca tane verimini değil, elde edilen tohumluğun fiziksel ve fizyolojik kalitesini de etkileyebilmektedir. Özellikle çiçeklenme, tohum gelişimi ve tane doldurma dönemlerinde meydana gelen su noksanlığı; embriyo ve endosperm gelişimini, asimilat taşınımını ve depo maddelerinin birikimini etkileyerek tohumluk kalitesinde değişikliklere neden olabilmektedir. Bunun yanında, çimlenme dönemindeki su noksanlığı tohumun su alımını ve metabolik süreçleri sınırlandırarak çimlenme, vigor ve erken fide gelişimini olumsuz etkileyebilmektedir.

Kuraklığın tohumluk kalitesi üzerindeki etkisinin büyüklüğü; tahıl türü, genotip, stresin şiddeti ve süresi ile meydana geldiği gelişme dönemine bağlı olarak değişmektedir. Bu nedenle kuraklık toleransının değerlendirilmesinde yalnızca tane veriminin değil; tohum ağırlığı, çimlenme, vigor, tarla çıkışı ve erken fide gelişimi gibi özelliklerin de birlikte ele alınması önem taşımaktadır. Ayrıca tohumluk üretimi sırasında meydana gelen kuraklık ile elde edilen tohumların sonraki çimlenme ve fide performansı arasındaki ilişkinin farklı tahıl türleri ve genotiplerde daha ayrıntılı olarak araştırılması gerekmektedir.

Sonuç olarak, değişen iklim koşullarında tahıl üretiminin sürdürülebilirliği açısından yalnızca yüksek tane veriminin korunması yeterli değildir. Kuraklık koşullarında fiziksel ve fizyolojik kalitesini koruyabilen, yüksek çimlenme ve vigor gösteren ve güçlü erken fide gelişimi sağlayabilen kaliteli tohumlukların üretimi, ıslah ve yetiştirme stratejilerinin temel hedeflerinden biri olmalıdır.

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ANADOLU YEREL BUĞDAYLARININ DÜŞÜK GİRDİLİ TARIM SİSTEMLERİNDEKİ POTANSİYELİ

THE POTENTIAL OF ANATOLIAN WHEAT LANDRACES IN LOW-INPUT AGRICULTURAL SYSTEMS

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ÖZET
Buğday, Anadolu'nun tarımsal geçmişi, beslenme kültürü ve bitkisel genetik kaynakları içerisinde özel bir yere sahiptir. Anadolu'nun farklı agroekolojik bölgelerinde uzun yıllar boyunca çiftçiler tarafından yetiştirilen yerel buğday popülasyonları, doğal seleksiyon ve çiftçi seleksiyonunun ortak etkisi altında şekillenmiş geniş bir genetik ve fenotipik çeşitlilik barındırmaktadır. Günümüzde yaygın olarak "ata tohumu" olarak da ifade edilen bu geleneksel materyaller; belirli çevrelere uzun süreli uyum göstermeleri, genetik çeşitliliklerini korumaları ve farklı biyotik ve abiyotik streslere karşı önemli varyasyon taşımaları nedeniyle sürdürülebilir tarım açısından yeniden önem kazanmaktadır. İklim değişikliğine bağlı olarak kuraklık ve sıcaklık streslerinin şiddetlenmesi, su kaynaklarının azalması, toprak verimliliğinin bozulması ve tarımsal girdi maliyetlerinin artması, daha az dış girdiye gereksinim duyan üretim sistemlerinin geliştirilmesini gerekli kılmaktadır. Gübre, sulama, pestisit ve enerji kullanımının sınırlandırıldığı düşük girdili tarım sistemlerinde yalnızca yüksek verim potansiyeli değil; su ve besin elementlerinin etkin kullanımı, çevresel streslere tolerans, hastalık direnci, yabancı otlarla rekabet, verim kararlılığı ve ürün kalitesi gibi özellikler de önem taşımaktadır. Anadolu yerel buğdayları özellikle kuraklık, düşük sıcaklık, sınırlı toprak verimliliği ve değişken yetiştirme koşullarına adaptasyon bakımından önemli bir genetik çeşitlilik sunmaktadır. Bununla birlikte yerel çeşitlerin modern çeşitlerden her koşulda daha üstün olduğunun kabul edilmesi doğru değildir. Modern çeşitler özellikle optimum yetiştirme koşullarında yüksek tane verimi, yatmaya dayanıklılık ve agronomik üniformite bakımından önemli avantajlara sahip olabilmektedir. Bu nedenle Anadolu yerel buğdaylarının gelecekteki önemi, doğrudan üretimde kullanılmalarının yanı sıra taşıdıkları adaptif özelliklerin modern çeşitlerin yüksek verim potansiyeliyle bütünleştirilmesinde yatmaktadır. Yerel çeşitlerin ve ata tohumlarının korunması, kapsamlı biçimde karakterize edilmesi ve modern ıslah programlarında etkin olarak değerlendirilmesi; düşük girdili, kaynak kullanım etkinliği yüksek, çevresel değişkenliklere uyum sağlayabilen ve iklim değişikliğine daha dayanıklı buğday üretim sistemlerinin geliştirilmesine önemli katkılar sağlayabilir.
Anahtar kelimeler: Buğday, yerel çeşit, sürdürülebilir tarım

ABSTRACT
Wheat holds a prominent position in the agricultural history, food culture, and plant genetic resources of Anatolia. Local wheat populations cultivated by farmers for generations across the diverse agroecological regions of Anatolia harbor substantial genetic and phenotypic diversity shaped by the combined effects of natural and farmer-mediated selection. These traditional genetic resources, commonly referred to as "ancestral seeds" in Türkiye, have recently regained considerable importance for sustainable agriculture due to their long-term adaptation to specific environments, maintenance of genetic diversity, and extensive variation in responses to various biotic and abiotic stresses. The increasing severity of drought and heat stresses associated with climate change, declining water availability, deterioration of soil fertility, and rising agricultural input costs have intensified the need for production systems that rely on fewer external inputs. In low-input agricultural systems, where fertilizer, irrigation, pesticide, and energy use is reduced, emphasis is placed not only on high yield potential but also on efficient water and nutrient utilization, tolerance to environmental stresses, disease resistance,

competitive ability against weeds, yield stability, and end-use quality. Anatolian wheat landraces represent a valuable reservoir of genetic diversity, particularly for adaptation to drought, low temperatures, limited soil fertility, and fluctuating growing conditions. Nevertheless, landraces should not be assumed to outperform modern cultivars under all environmental and management conditions. Modern cultivars may provide substantial advantages in grain yield, lodging resistance, and agronomic uniformity, particularly under optimal growing conditions. Therefore, the future importance of Anatolian wheat landraces lies not only in their direct use in agricultural production but also in integrating their adaptive traits with the high-yield potential of modern cultivars. The conservation, comprehensive characterization, and effective utilization of landraces and ancestral genetic resources in modern breeding programs could make a significant contribution to developing low-input, resource-efficient wheat production systems capable of adapting to environmental variability and increasing resilience to climate change.
Keywords: Wheat, landrace, sustainable agriculture

GİRİŞ

Buğday, insanlık tarihinin en eski kültür bitkilerinden biri olup kültüre alınması yaklaşık 12.000 yıl önce başlamıştır ve insanlık tarihinde bir dönüm noktası olarak kabul edilmektedir (Tanno ve Willcox, 2006). Bereketli Hilal'in kuzey kesiminde yer alan Anadolu'da yerleşik hayata geçiş ve tarımın başlaması, buğdayın kültüre alınmasıyla eş zamanlı gerçekleşmiştir (Atar, 2017). Bu tarihsel süreç, Anadolu'da gerek ekmeklik gerekse makarnalık buğdaylarda zengin genetik ve fenotipik çeşitliliğin oluşmasında önemli pay sahibi olmuştur (Karagöz ve Zencirci, 2005; Baloch ve ark., 2017).

Yerel çeşitler, tarihsel bir kökeni olan, kendine özgü bir kimliğe sahip, genellikle genetik çeşitlilik gösteren ve yerel koşullara uyum sağlamış, ayrıca çiftçilerin tohum seçimi ve tarla yönetimi uygulamalarıyla ve bilgi birikimiyle ilişkilendirilen, kültür bitkilerinin dinamik popülasyonları olarak tanımlanmaktadır (Azez ve ark., 2018). Yerel iklim koşullarına adapte olmuş, zaman süzgecinden geçerek kuşaktan kuşağa aktarılarak varlığını sürdürmüş ve çiftçilerin ihtiyaç duydukları tohumluğu üretilebilmelerine olanak sağlayan yerel çeşitler, sürdürülebilir tarımın ekolojik, ekonomik ve sosyo-kültürel düzeylerinde önemli avantajlar sağlamaktadır (Kayış ve ark., 2025).

Yerel çeşitler, bünyelerinde barındırdıkları genotipik çeşitlilik nedeniyle çok sayıda özellik bakımından geniş bir varyasyon sergileyebilmektedir. Bu varyasyon, söz konusu çeşitlerin yetiştirildikleri çevre koşullarında doğal seleksiyonun yanı sıra, sınırlı ölçüde geleneksel çiftçiler tarafından gerçekleştirilen seleksiyonun etkisiyle zaman içerisinde şekillenmiştir. Bu nedenle yerel çeşitler; soğuğa, yüksek sıcaklıklara ve kuraklığa tolerans; başaklanma ve olgunlaşma zamanı ile tane dolum süresi; bitki patojenlerinin neden olduğu hastalıklara dayanıklılık ve diğer olumsuz çevresel stres faktörlerine tolerans gibi arzu edilen özellikler bakımından önemli bir genetik çeşitlilik kaynağı niteliğindedir (Jaradat, 2011).

Anadolu yerel buğdaylarının önemli bir özelliği, çok farklı yetiştirme çevrelerinde uzun süre üretimde kalmış olmalarıdır. Türkiye'de buğday yetiştiriciliği; kıyı bölgelerinden yüksek rakımlı Doğu Anadolu'ya, yüksek yağışlı geçiş bölgelerinden kurak Orta ve Güneydoğu Anadolu koşullarına kadar oldukça geniş bir ekolojik aralıkta gerçekleştirilmektedir. Bu ekolojik farklılaşma; bitki boyu, başak özellikleri, çiçeklenme zamanı, tane büyüklüğü, kışa dayanıklılık, tane kalitesi ve diğer adaptif özellikler bakımından geniş varyasyon oluşmasına neden olmuştur (Zencirci & Karagöz, 2005; Alsaleh et al., 2016). Bitkilerdeki tüm bileşiklerin içeriği, genotip ve çevrenin yanı sıra bunların etkileşimlerinden de etkilenmektedir. Bununla birlikte, bu farklı parametreler üzerindeki etki düzeyi, bitki materyalinin seçimine, yetiştirme ortamına ve yetiştirme uygulamalarına bağlıdır (Johansson ve ark. 2014).

Türkiye genelinde gerçekleştirilen geniş ölçekli örnekleme çalışmalarında 59 ilden 1600'den fazla çiftçinin tarlalarından yerel buğday materyalleri toplanmış ve siyez, gernik, topbaş, makarnalık ve ekmeklik buğdayları kapsayan 95 farklı morfotip tanımlanmıştır. Bununla birlikte günümüzde belirlenen çeşitliliğin yaklaşık bir asır önce kaydedilmiş buğday çeşitliliğiyle karşılaştırılması, bazı bölgelerde önemli düzeyde genetik erozyon meydana geldiğini göstermektedir (Morgounov et al., 2016).

Yerel çeşitler, yoğun girdili üretim sistemlerine uyumlu Yeşil Devrim'in yarı bodur modern çeşitlerinin yaygınlaşmasıyla bitkisel üretimdeki yerlerini büyük ölçüde kaybetmiştir (Royo ve ark., 2009). Bununla birlikte yerel çeşitler, yoğun girdili üretim sistemlerine uyumlu Yeşil Devrim'in yarı bodur modern çeşitlerinin yaygınlaşmasıyla bitkisel üretimdeki yerlerini büyük ölçüde kaybetmiştir (Lopez ve ark.,

2015). Bu durum yerel çeşitlerin yalnızca kültürel miras olarak değil, geleceğin sürdürülebilir buğday üretim sistemleri için önemli genetik kaynaklar olarak değerlendirilmesini zorunlu kılmaktadır.

DÜŞÜK GİRDİLİ TARIM SİSTEMLERİNDE ANADOLU YEREL BUĞDAYLARININ POTANSİYELİ

Düşük girdili tarım sistemleri, sentetik gübre, pestisit, sulama suyu, enerji ve diğer dış girdilerin kullanımının sınırlandırıldığı veya daha etkin hâle getirildiği üretim yaklaşımlarını kapsamaktadır. Bu sistemlerde yalnızca birim alandan maksimum verim elde etmek değil, kullanılan kaynak başına üretimin artırılması ve çevresel sürdürülebilirliğin sağlanması amaçlanmaktadır. Bu nedenle düşük girdili koşullara uygun çeşitlerden beklenen özellikler de yüksek girdili sistemler için geliştirilen çeşitlerden kısmen farklılaşmaktadır. Kök sisteminin gelişmiş olması, su ve besin elementlerinden etkin yararlanma, yabancı otlarla rekabet, hastalık dayanıklılığı, çevresel değişkenliğe tolerans ve kabul edilebilir düzeyde verim kararlılığı bu özelliklerin başında gelmektedir (Ceccarelli, 1996; Wolfe et al., 2008; Lammerts van Bueren et al., 2011).

Kuraklık, Türkiye'de özellikle Orta Anadolu ve Güneydoğu Anadolu'da buğday üretimini sınırlandıran en önemli abiyotik streslerden biridir. Yerel buğdayların uzun süre yağışa dayalı koşullarda yetiştirilmesi; fenolojik plastisite, farklı kök mimarileri, erken gelişme, biyokütle dağılımı ve su kullanım stratejileri gibi özelliklerde geniş bir varyasyon oluşmasına katkı sağlamıştır. Türkiye kökenli yerel makarnalık ve ekmeklik buğdaylarda çevresel stres toleransı ve adaptif özellikler bakımından önemli farklılıkların bulunması, bu materyallerin kuraklık ıslahında kullanılabilecek gen kaynakları olduğunu göstermektedir (Damania et al., 1996, 1997; Morgounov et al., 2016; Kaya, 2021; Demirdogen ve ark., 2024).

Düşük girdili üretimin bir diğer önemli bileşeni azotlu gübre kullanımının azaltılmasıdır. Azotlu gübrelerin üretimi için gereken enerji maliyeti oldukça yüksek olup (Smil, 2001), azotlu gübreleme tahıl temelli üretim sistemlerinde çoğu zaman en yüksek enerji girdilerinden birini oluşturmaktadır (Crews & Peoples, 2004). Yerel buğdaylar arasında kök gelişimi, biyokütle üretimi, tane protein oranı ve besin elementi alımı bakımından geniş varyasyon bulunmasına rağmen, modern çeşitlerin bazı koşullarda azot kullanım etkinliği bakımından daha başarılı olabileceği de bilinmektedir. Bu nedenle yerel çeşitlerin düşük azot koşullarındaki önemi, doğrudan genelleştirilebilecek bir üstünlükten çok, üstün genotiplerin ve faydalı allellerin belirlenebileceği geniş bir genetik havuz oluşturmalarından kaynaklanmaktadır (Fageria, 2008; Elbasyoni, 2019).

Yerel çeşitlerin birçok modern yarı bodur çeşide kıyasla daha uzun bitki yapısına sahip olması da düşük girdili üretimde hem avantaj hem dezavantaj oluşturabilmektedir. Uzun bitki boyu, yüksek biyokütle ve hızlı toprak kapatma özelliği özellikle herbisit kullanımının sınırlandırıldığı sistemlerde yabancı otlarla rekabeti artırabilir. Buna karşılık yüksek bitki boyu, uygun nem ve besin koşullarında yatma riskini yükseltebilir. Bu nedenle düşük girdili sistemlere uygun yeni çeşitlerin geliştirilmesinde yerel materyalin yabancı ot rekabeti gibi olumlu özellikleri ile modern çeşitlerin yatmaya dayanıklılık özelliklerinin birleştirilmesi önemli olabilir (Wolfe ve ark., 2008; Bertholdsson ve ark., 2016).

Yerel buğdayların dikkat çekici yönlerinden biri de tane ve ürün kalitesidir. Anadolu'da uzun yıllardır yetiştirilen yerel buğdayların önemli bir bölümü geleneksel ekmek, bulgur, erişte ve diğer yöresel ürünlerin üretiminde kullanılmaktadır. Yerel materyaller arasında tane iriliği, camsılık, protein oranı, gluten özellikleri, pigment içeriği ve diğer kalite parametreleri bakımından geniş varyasyon bulunmaktadır. Özellikle Anadolu'nun geleneksel makarnalık buğdaylarından Kunduru materyalinde yüksek düzeyde fenotipik ve kalite çeşitliliği belirlenmiştir. Bu özellikler, yerel buğdayların düşük girdili sistemlerde yalnızca verim odaklı değil, yüksek katma değerli ürünlerin hammaddesi olarak da değerlendirilmesine olanak sağlamaktadır (Akçura, 2009; Alsaleh ve ark., 2016; Zencirci, 2008).

YEREL BUĞDAY GENETİK KAYNAKLARININ KORUNMASI VE ISLAH POTANSİYELİ

Anadolu yerel buğdayları, uzun yıllar boyunca farklı ekolojik koşullar ve çiftçi seleksiyonu altında şekillenmiş geniş bir genetik çeşitliliğe sahip önemli bitki genetik kaynaklarıdır (Karagöz, 2014). Türkiye'de bu çeşitliliğin korunmasına yönelik toplama ve kayıt altına alma çalışmaları uzun bir geçmişe sahip olup, farklı dönemlerde gerçekleştirilen araştırmalar yerel buğday genetik kaynaklarının belirlenmesi ve ex situ koşullarda muhafaza edilmesine önemli katkılar sağlamıştır (Harlan, 1950; Damania ve ark., 1996; Karagöz, 1996; Qualset ve ark., 1997; Tan, 2002; Karagöz ve Zencirci, 2005; Akçura ve Topal, 2006; Giuliani ve ark., 2009). Bu çalışmalar sonucunda Anadolu'nun geçmişte sahip

olduğu yerel buğday çeşitliliğinin önemli bir bölümü, Türkiye'de ve farklı ülkelerde bulunan gen bankası koleksiyonlarında korunmaktadır. Bununla birlikte, gen bankalarında gerçekleştirilen ex situ korumanın yanı sıra, yerel çeşitlerin yetiştirildikleri alanlarda korunması genetik çeşitliliğin devamlılığı açısından önem taşımaktadır. Yerel çeşitlerin güncel durumunun ve yetiştirildikleri bölgelerin belirlenmesine yönelik envanter çalışmalarının, in situ/on-farm koruma stratejilerinin geliştirilmesi ve bu genetik kaynakların sürdürülebilir kullanımının sağlanması açısından gerekli olduğu bildirilmektedir (Negri ve ark., 2012). Bu nedenle Anadolu yerel buğdaylarının hem gen bankalarında hem de çiftçi koşullarında korunması, sahip oldukları genetik çeşitliliğin gelecek nesillere aktarılması ve gelecekteki buğday ıslah çalışmalarında kullanılabilmesi açısından önem taşımaktadır.

Yerel buğdayların korunmasının yanı sıra agronomik, fizyolojik, kalite ve adaptasyon özellikleri bakımından karakterize edilmesi de büyük önem taşımaktadır. Anadolu yerel buğdaylarında farklı yükselti ve yetiştirme bölgelerine bağlı olarak önemli fenotipik farklılıkların bulunması, bu materyallerin farklı çevre koşullarına adaptasyon bakımından geniş bir varyasyon taşıdığını göstermektedir (Karagöz ve Zencirci, 2005; Damania ve ark., 1996). Bu çeşitlilik, özellikle düşük girdili ve çevresel streslerin belirgin olduğu üretim sistemleri açısından değerli genotiplerin belirlenmesine olanak sağlamaktadır.

Moleküler markör ve genomik teknolojilerdeki gelişmeler, yerel buğdaylarda bulunan genetik çeşitliliğin daha ayrıntılı olarak ortaya çıkarılmasına olanak sağlamıştır. DArTseq, SNP ve diğer yüksek çözünürlüklü moleküler yaklaşımlarla gerçekleştirilen çalışmalar, Anadolu ve yakın çevresindeki buğday materyallerinde geniş genomik varyasyon bulunduğunu ve bu varyasyonun ıslah çalışmalarında değerlendirilebileceğini göstermektedir (Sehgal ve ark., 2016; Baloch ve ark., 2017; Alsaleh ve ark., 2022).

Bu nedenle Anadolu yerel buğdaylarının korunması, yalnızca mevcut genetik çeşitliliğin muhafaza edilmesiyle sınırlı kalmamalı, bu materyallerin modern buğday ıslahına entegrasyonu da hedeflenmelidir. Özellikle kuraklık toleransı, azot kullanım etkinliği, hastalık direnci, yabancı otlarla rekabet, tane kalitesi ve verim kararlılığı bakımından üstün genotiplerin belirlenmesi, düşük girdili koşullara uygun yeni çeşitlerin geliştirilmesine katkı sağlayabilir. Böylece yerel materyallerin adaptif özellikleri ile modern çeşitlerin yüksek verim ve agronomik uygunluk özelliklerinin bir araya getirilmesi mümkün olabilir (Ceccarelli, 1996; Wolfe et al., 2008; Sehgal et al., 2016).

SONUÇ

Anadolu yerel buğdayları, uzun süreli doğal ve çiftçi seleksiyonu sonucunda farklı yetiştirme çevrelerine uyum sağlamış ve geniş genetik çeşitlilik kazanmış önemli bitkisel genetik kaynaklardır. Anadolu'nun iklim, yükselti ve toprak özellikleri bakımından gösterdiği çeşitlilik, yerel buğday popülasyonlarında fenoloji, bitki morfolojisi, stres toleransı ve kalite özellikleri bakımından önemli varyasyonların ortaya çıkmasına katkıda bulunmuştur (Karagöz & Zencirci, 2005; Karagöz, 2014).

Düşük girdili tarım sistemlerinde çeşitlerden beklenen özellikler, yalnızca yüksek tane verimi ile sınırlı değildir. Su ve besin elementlerinden etkin yararlanma, biyotik ve abiyotik streslere tolerans, yabancı otlarla rekabet ve değişken çevre koşullarında verim kararlılığı da önem taşımaktadır. Yerel buğdayların sahip olduğu genetik çeşitlilik, bu özellikler bakımından uygun genotiplerin belirlenmesi açısından önemli bir kaynak oluşturmaktadır (Ceccarelli, 1996; Wolfe et al., 2008).

Anadolu yerel buğdaylarının düşük girdili tarım açısından temel değeri, modern çeşitlere doğrudan alternatif oluşturmalarından çok, gelecekteki ıslah çalışmalarında kullanılabilecek genetik çeşitliliği barındırmalarından kaynaklanmaktadır. Yerel materyallerde bulunan adaptif özelliklerin modern çeşitlerin yüksek verim ve agronomik özellikleriyle birleştirilmesi, daha az dış girdiye ihtiyaç duyan ve çevresel değişkenliğe daha iyi uyum sağlayabilen yeni çeşitlerin geliştirilmesine katkı sağlayabilir (Ceccarelli, 1994, 1996; Sehgal et al., 2016).

Sonuç olarak Anadolu yerel buğdaylarının korunması, karakterize edilmesi ve ıslah programlarında etkin biçimde değerlendirilmesi, düşük girdili buğday üretiminin sürdürülebilirliği açısından önem taşımaktadır. Genetik kaynakların ex situ ve on-farm yöntemlerle korunması ile agronomik, fizyolojik ve genomik karakterizasyon çalışmalarının birlikte yürütülmesi, bu materyallerde bulunan faydalı genetik varyasyonun geleceğin buğday çeşitlerine aktarılmasına olanak sağlayacaktır (Morgounov et al., 2016; Baloch et al., 2017; Alsaleh et al., 2022).

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RESEARCH ON SITOPHILUS ORYZAE IN WHEAT: A BIBLIOMETRIC ANALYSIS OF SCIENTIFIC OUTPUT, THEMATIC TRENDS, AND COLLABORATION NETWORKS

SITOPHILUS ORYZAE VE BUĞDAYLA İLİŞKİLİ ARAŞTIRMALARIN BİBLİYOMETRİK ANALİZİ: BİLİMSEL ÜRETİM, TEMATİK EĞİLİMLER VE İŞ BİRLİĞİ AĞLARI

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ÖZET

Bu araştırmanın amacı, *Sitophilus oryzae* L. (pirinç biti) ile buğday ilişkili literatürün bilimsel üretim yapısını, gelişim eğilimlerini, atıf örüntülerini, kavramsal temalarını ve iş birliği ağlarını bibliyometrik yöntemlerle incelemektir. Veriler, Web of Science Core Collection veri tabanında 5 Temmuz 2026 tarihinde gerçekleştirilen taramadan elde edilmiştir. *Sitophilus oryzae* ya da rice weevil terimleri ile buğdayı karşılayan terimlerin birlikte kullanıldığı sorguda başlangıçta 854 yayına ulaşılmış; yalnızca İngilizce makalelerin seçilmesiyle 1946-2026 dönemini kapsayan 796 çalışma analize alınmıştır. Veriler R programlama diliyle çözümlenmiş; yıllık yayın üretimi, yaşam döngüsü, üretken yazar, ülke, kurum ve dergiler, atıf yapısı, yazar anahtar kelimeleri, tematik eğilimler ve ortak yazarlık ağları incelenmiştir. Bulgular, 2000'li yıllardan sonra artan yayın üretiminin özellikle 2015 sonrasında hızlandığını ve 2021'de 41 yayınla en yüksek düzeye ulaştığını göstermiştir. Lojistik yaşam döngüsü modeli, alanın henüz doygunluğa ulaşmadığına ve büyüme evresini sürdürdüğüne işaret etmiştir. Athanassiou CG, Kavallieratos NG ve Arthur FH en üretken yazarlar; Yunanistan ve ABD ise en görünür ülkeler olmuştur. Journal of Stored Products Research, hem yayın üretimi hem de yüksek atıflı çalışmalar bakımından alanın başlıca yayın platformu olarak belirlenmiştir. En üretken kurumlar University of Thessaly, Agricultural University of Athens ve Benaki Phytopathological Institute olarak saptanmıştır. Atıf analizi, bitkisel yağlar, fosfin direnci, diyatom toprağı ve depolama koşullarının etkili araştırma eksenleri olduğunu göstermiştir. Bulgular yalnızca Web of Science kapsamındaki İngilizce makaleleri yansıttığından bu sınırlılık gözetilerek dikkatle yorumlanmalıdır. Kavramsal yapı; *S. oryzae*, buğday, *Tribolium* türleri, *Rhyzopertha dominica* ve diyatom toprağı çevresinde şekillenmiştir. Son yıllarda direnç, toksisite, sıcaklık, spinosad ve alternatif mücadele yöntemleri daha görünür hâle gelmiştir. Türkiye 45 kayıtla ilk 20 ülke arasında yer almasına karşın uluslararası iş birliği ağında çevresel bir konumda kalmıştır. Sonuçlar, literatürün entomoloji merkezli olmakla birlikte tarım, gıda bilimi, bitki bilimleri ve sürdürülebilir zararlı yönetimiyle ilişkili disiplinler arası bir yapıda geliştiğini göstermektedir. Türkiye merkezli araştırmaların uluslararası ortaklıkları artırması ve çevre dostu kontrol yaklaşımlarına yönelmesi önerilmektedir.

Anahtar kelimeler: *S. oryzae*, pirinç biti, buğday, depo zararlıları, bibliyometrik analiz, zararlı yönetimi

ABSTRACT

This study examined the scientific output, publication trends, citation patterns, conceptual themes, and collaboration networks of research on *Sitophilus oryzae* L. (rice weevil) and wheat using bibliometric methods. Data were retrieved from the Web of Science Core Collection through a search conducted on 5 July 2026. The search combined the terms *S. oryzae* or rice weevil with terms referring to wheat. It initially yielded 854 records; after limiting the results to English-language articles, 796 publications covering the period 1946-2026 were included. Data were analyzed in R to assess annual scientific production, publication life cycle, prolific authors, countries, institutions, and journals, citation structure, author keywords, thematic trends, and co-authorship networks. Results showed that publication output increased after 2000, accelerated after 2015, and peaked at 41 articles in 2021. The logistic life-cycle model indicated that the field has not yet reached saturation and remains in a growth phase. Athanassiou CG, Kavallieratos NG, and Arthur FH were the most prolific authors, while Greece

and the United States were the most prominent countries. Journal of Stored Products Research emerged as the leading outlet in both publication output and highly cited studies. The University of Thessaly, Agricultural University of Athens, and Benaki Phytopathological Institute were the most productive institutions. Citation analysis identified botanical oils, phosphine resistance, diatomaceous earth, and storage conditions as influential research areas. The conceptual structure centered on *S. oryzae*, wheat, *Tribolium* species, *Rhyzopertha dominica*, and diatomaceous earth, whereas resistance, toxicity, temperature, spinosad, and alternative control methods gained visibility in recent years. Türkiye ranked among the top 20 countries with 45 records but occupied a peripheral position in the international collaboration network. Overall, the literature remains entomology-centered while displaying interdisciplinary links with agriculture, food science, plant sciences, and sustainable pest management. Strengthening international collaboration and environmentally friendly control research is recommended, particularly for Türkiye.
Keywords: *S. oryzae*, rice weevil, wheat, stored-product pests, bibliometric analysis, pest management.

GİRİŞ

Depolanmış tahılların korunması, yalnızca tarımsal üretimin devamı açısından değil, gıda güvenliği, ürün kalitesi ve ekonomik kayıpların azaltılması bakımından da stratejik bir konudur. Gıda güvenliği; bireylerin her zaman yeterli, güvenli ve besleyici gıdaya fiziksel ve ekonomik olarak erişebilmesiyle ilişkilendirilmektedir (FAO, 2008). Bu nedenle gıdanın üretimden tüketime kadar geçen süreçte korunması, özellikle buğday gibi temel tahıllarda, gıda arzının sürekliliği açısından kritik önem taşımaktadır. Hasat sonrası dönemde ortaya çıkan zararlı kaynaklı kayıplar, ürün miktarında azalmaya, kalite bozulmasına, ticari değer kaybına ve tüketici sağlığı açısından risklerin artmasına neden olabilmektedir.

Depolanmış ürün zararlıları içinde *S. oryzae* L. (Coleoptera: Curculionidae), yaygınlığı ve zarar potansiyeli nedeniyle öne çıkan türlerden biridir. Literatürde pirinç biti olarak adlandırılmasına karşın bu zararlı yalnızca pirinçle sınırlı değildir; buğday, arpa, mısır ve sorgum gibi farklı tahıl ürünlerinde de zarar oluşturabilmektedir (Kandel et al., 2021). Pirinç bitinin önemli bir depolanmış tahıl zararlısı olarak değerlendirilmesinde, ergin ve larva dönemlerinin ürüne doğrudan zarar vermesi belirleyicidir. Özellikle larvaların dane içinde gelişmesi, zararın dışarıdan kolaylıkla fark edilmesini güçleştirmekte ve bulaşık danelerin ayıklanmasını zorlaştırmaktadır. Bu yönüyle *S. oryzae*, depolanmış buğdayda hem nicel hem de nitel kayıplara yol açan başlıca zararlılar arasında kabul edilmektedir (Flinn et al., 2007; Hagstrum et al., 2012).

Buğdayın depolanması sırasında zararlıların gelişimi; sıcaklık, nem (ortam ve tane), depolama süresi, hijyen koşulları ve mücadele yöntemleri gibi çok sayıda faktörden etkilenmektedir. Depo ortamındaki sıcaklık ve nem değişimleri, böcek popülasyonlarının çoğalma hızını ve zararın şiddetini belirleyebilmektedir. Bu nedenle depolanmış ürün zararlılarıyla mücadelede yalnızca kimyasal uygulamalara dayalı bir yaklaşım yeterli görülmemekte; izleme, erken tespit, hijyen, sıcaklık-nem yönetimi ve entegre zararlı yönetimi uygulamalarının birlikte ele alınması önerilmektedir (Hagstrum et al., 2012). Bununla birlikte fosfin başta olmak üzere fumigantların uzun yıllardır yoğun biçimde kullanılması, direnç gelişimi, kalıntı riski ve çevresel etkiler gibi sorunları gündeme getirmiştir (Yılmaz Doğu & Emekci, 2026). Bu durum, *S. oryzae* ile mücadelede alternatif ve çevre dostu yöntemlere yönelik araştırmaların artmasına zemin hazırlamıştır.

Son yıllarda diyatom toprağı, bitkisel yağlar, uçucu yağlar, sıcaklık uygulamaları, kontrollü atmosfer, hipoksi, spinosad ve diğer düşük riskli mücadele yaklaşımları, depolanmış ürün zararlıları literatüründe daha görünür hâle gelmiştir. Diyatom toprağına ilişkin çalışmalar, bu materyalin böcek kutikulasındaki mumsu tabakayı aşındırarak dehidrasyona yol açması nedeniyle fiziksel etki mekanizmasına sahip doğal bir insektisit olarak değerlendirildiğini göstermektedir (Korunić, 1998). Pirinç bitine karşı buğday ve arpada yürütülen çalışmalar, diyatom toprağının etkinliğinin uygulama dozu, sıcaklık, nem, tane nemi ve zararlı türüne göre değişebildiğini ortaya koymuştur (Athanassiou et al., 2005; Yılmaz Doğu & Emekci, 2026). Benzer biçimde bitkisel kökenli bileşikler ve uçucu yağlar da depolanmış ürün zararlılarına karşı alternatif mücadele olanakları kapsamında ele alınmaktadır (Kim et al., 2003; Shaaya et al., 1997). Bu araştırma yönelimleri, alanın yalnızca klasik kimyasal mücadele ekseninde değil, sürdürülebilir zararlı yönetimi çerçevesinde de geliştiğini göstermektedir.

Pirinç biti ve buğday ilişkili literatür, entomoloji merkezli olmakla birlikte tarım, gıda bilimi, bitki koruma, depolama teknolojileri ve sürdürülebilir üretim gibi farklı disiplinlerle kesişen bir yapıya

sahiptir. Bu çok disiplinli yapı, alandaki bilimsel üretimin yalnızca yayın sayıları üzerinden değil; etkili yazarlar, ülkeler, kurumlar, dergiler, atıf örüntüleri, anahtar kelimeler ve iş birliği ağları üzerinden de incelenmesini gerekli kılmaktadır. Çünkü belirli bir araştırma alanının gelişim çizgisi, hangi konuların merkezde yer aldığı, hangi temaların yükselişe geçtiği ve hangi ülkelerin ya da kurumların bilgi üretiminde belirleyici olduğu ancak bütüncül bir bilim haritalama yaklaşımıyla anlaşılabilir.

Bibliyometrik analiz, büyük ölçekli akademik literatürü nicel göstergeler aracılığıyla incelemeye olanak tanıyan güçlü bir yöntemdir. Bu yaklaşım; yayın üretimi, atıf ilişkileri, ortak yazarlık ağları, ülke ve kurum iş birlikleri, kavramsal yapı ve tematik eğilimlerin sistematik biçimde değerlendirilmesine imkân sağlar (Zupic & Čater, 2015). Özellikle bilim haritalama teknikleri, araştırma alanlarının zaman içinde nasıl geliştiğini, hangi kavramların merkezî konuma geldiğini ve hangi konuların yeni eğilimler olarak ortaya çıktığını görünür kılar. R tabanlı bibliometrix paketi gibi araçlar, bibliyometrik verilerin düzenlenmesi, çözümlenmesi ve görselleştirilmesi için kapsamlı bir iş akışı sunmaktadır (Aria & Cuccurullo, 2017). Bu yönüyle bibliyometrik analiz, pirinç biti ve buğday ilişkili literatürün uzun dönemli gelişimini değerlendirmek için uygun bir yöntemsel çerçeve sağlamaktadır.

Bu alanda pirinç bitinin biyolojisi, depolanmış tahıllardaki zararı, fumigantlara duyarlılığı, direnç gelişimi ve alternatif mücadele yöntemleri üzerine çok sayıda deneysel çalışma bulunmaktadır. Ancak bu çalışmaların önemli bir kısmı belirli bir mücadele yöntemi, belirli bir zararlı türü, belirli bir ürün ya da belirli bir çevresel koşul üzerine odaklanmaktadır. Buna karşılık pirinç biti ve buğday eksenindeki bilimsel üretimin tarihsel gelişimini, etkili yayınları, üretken araştırmacıları, kurumsal ve ülkesel katkıları, kavramsal temaları ve iş birliği ağlarını birlikte değerlendiren bibliyometrik çalışmalar sınırlıdır. Bu eksiklik, alanın genel yapısının, araştırma boşluklarının ve gelecekte güçlenebilecek tematik yönelimlerin belirlenmesini zorlaştırmaktadır.

Bu araştırmanın amacı, pirinç biti ve buğday ilişkili çalışmaların bilimsel üretim yapısını, kavramsal gelişimini, atıf örüntülerini ve iş birliği ağlarını bibliyometrik analiz yoluyla incelemektir. Bu amaç doğrultusunda aşağıdaki araştırma sorularına yanıt aranmıştır:

1. Pirinç bitive buğday ilişkili çalışmaların yıllara göre yayın üretim eğilimi nasıldır?
2. Bu alanda en üretken yazarlar, ülkeler/bölgeler, kurumlar ve kaynaklar/dergiler hangileridir?
3. Alandaki en çok atıf alan yayınlar ve etkili çalışmalar hangi konular etrafında yoğunlaşmaktadır?
4. Yazar anahtar kelimelerine göre alanın kavramsal yapısı, temel temaları ve trend konuları nelerdir?
5. Ülke ve yazar iş birliği ağları, alandaki bilimsel iş birliği örüntüleri hakkında ne göstermektedir?

YÖNTEM

Bu araştırma, pirinç biti ve buğday ilişkili bilimsel yayınların gelişimini, kavramsal yapısını, atıf örüntülerini ve iş birliği ağlarını incelemek amacıyla bibliyometrik araştırma deseniyle tasarlanmıştır (Donthu et al., 2021; Zupic & Čater, 2015). Bibliyometrik analiz, belirli bir araştırma alanında üretilen bilimsel yayınların yıllara göre dağılımını, üretken yazar, ülke, kurum ve kaynaklarını, atıf yapılarını, anahtar kelime örüntülerini ve bilimsel iş birliği ağlarını nicel göstergeler aracılığıyla incelemeye olanak sağlayan bir yöntemdir. Bu doğrultuda araştırmada tanımlayıcı bibliyometrik göstergeler, ağ analizleri ve tematik analizler birlikte kullanılmıştır.

Veri Kaynağı ve Arama Stratejisi

Araştırmanın veri kaynağını Web of Science Core Collection veri tabanında indekslenen yayınlar oluşturmuştur. Veri tabanı taraması 5 Temmuz 2026 tarihinde saat 23.30'da gerçekleştirilmiştir. Tarama sürecinde pirinç biti ile buğdayı karşılayan terimler birlikte kullanılmıştır. Araştırmanın tekrarlanabilirliğini sağlamak amacıyla kullanılan arama sorgusu aşağıda verilmiştir:

TS = ((“*Sitophilus oryzae*” OR “rice weevil”) AND (“*Triticum aestivum*” OR wheat OR “common wheat”))

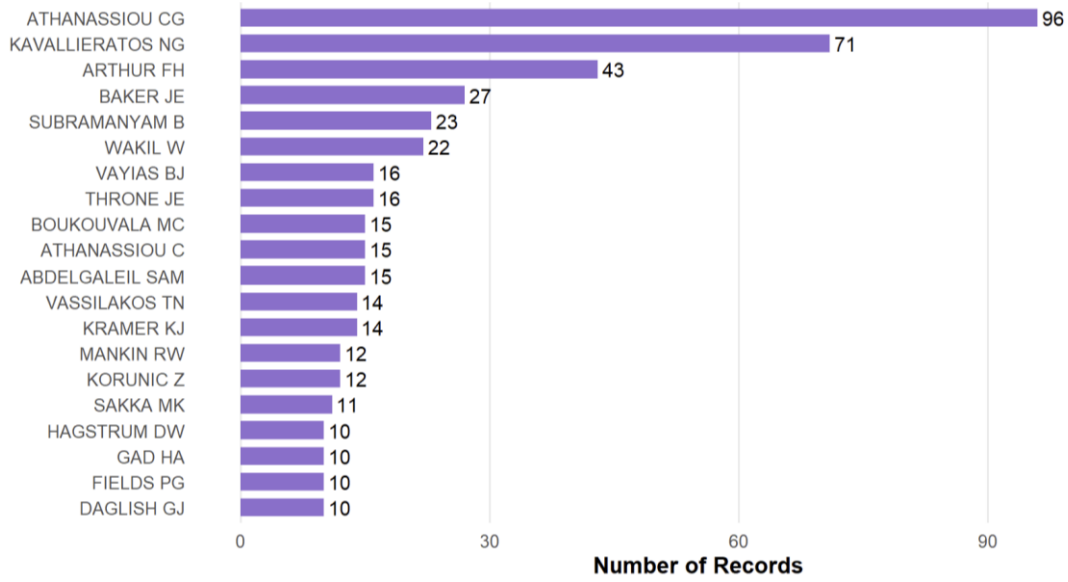
İlk tarama sonucunda 854 yayına ulaşılmıştır. Daha sonra araştırmanın kapsamı doğrultusunda dahil etme ve dışlama ölçütleri uygulanmıştır. Dahil etme ölçütleri; yayının Web of Science Core Collection veri tabanında indekslenmiş olması, İngilizce yayımlanmış olması ve belge türünün makale olması şeklinde belirlenmiştir. Kitap bölümleri, bildiriler, derlemeler, editoryal materyaller, notlar, erken erişim dışındaki uygun olmayan kayıtlar ve İngilizce dışındaki yayınlar analiz kapsamı dışında bırakılmıştır. Böylece analizlerin yalnızca hakemli makaleler üzerinden yürütülmesi ve veri setinin daha homojen bir

yapıya sahip olması amaçlanmıştır. Bu ölçütlerin uygulanmasının ardından nihai veri seti 1946-2026 dönemini kapsayan 796 makaleden oluşmuştur.

Elde edilen bibliyografik veriler Web of Science veri tabanından uygun dosya formatında dışa aktarılmış ve R programlama dili kullanılarak analiz edilmiştir. Analiz sürecinde yıllık yayın üretimi, yayınların yaşam döngüsü, en üretken yazarlar, ülkeler, kurumlar ve kaynaklar/dergiler belirlenmiştir. Ayrıca en çok atıf alan yayınlar, yazar anahtar kelimeleri, tematik eğilimler ve kavramsal yapı incelenmiştir. Bilimsel iş birliği örüntülerini ortaya koymak amacıyla ülke ve yazar düzeyinde ortak yazarlık ağları analiz edilmiştir. Bu analizler aracılığıyla alanın tarihsel gelişimi, temel araştırma eksenleri, yükselen temaları ve uluslararası iş birliği yapısı bütüncül biçimde değerlendirilmiştir.

ARAŞTIRMA BULGULARI VE TARTIŞMA

Şekil 1, alandaki en üretken 20 yazarı göstermektedir. Athanassiou CG 96 kayıtla en üretken yazar olurken, onu 71 kayıtla Kavallieratos NG ve 43 kayıtla Arthur FH izlemiştir. Bu bulgu, literatürün görece sınırlı sayıda yüksek üretkenliğe sahip araştırmacılar tarafından şekillendirildiğini göstermektedir.

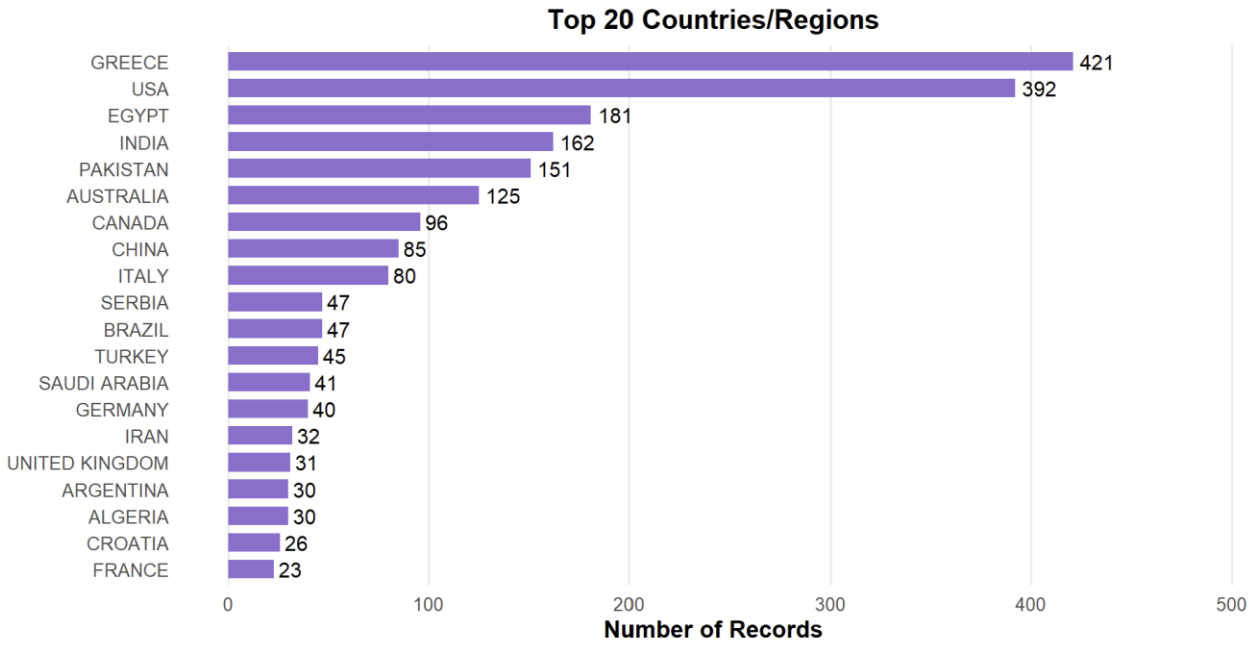


Şekil 1. Alandaki En Üretken 20 Yazar

Şekil 2'e göre Türkiye, yazar adreslerine dayalı ülke/bölge dağılımında 45 kayıt ile ilk 20 ülke arasında yer almaktadır. Türkiye bu sayı ile Yunanistan, ABD, Mısır, Hindistan, Pakistan, Avustralya, Kanada, Çin, İtalya, Sırbistan ve Brezilya'nın ardından gelmektedir. Bu bulgu, Türkiye'nin pirinç biti ve buğday ilişkili çalışmalar alanında görünür bir katkı sunduğunu, ancak alanın özellikle Yunanistan ve ABD merkezli daha yoğun bir üretim yapısına sahip olduğunu göstermektedir. Türkiye'de depolanmış buğday zararlıları ve diyatom toprağı gibi alternatif mücadele yöntemleri üzerine yürütülen çalışmaların bulunması, uluslararası iş birlikleri için uygun bir araştırma zemininin mevcut olduğunu göstermektedir (Yılmaz Doğu & Emekci, 2026).

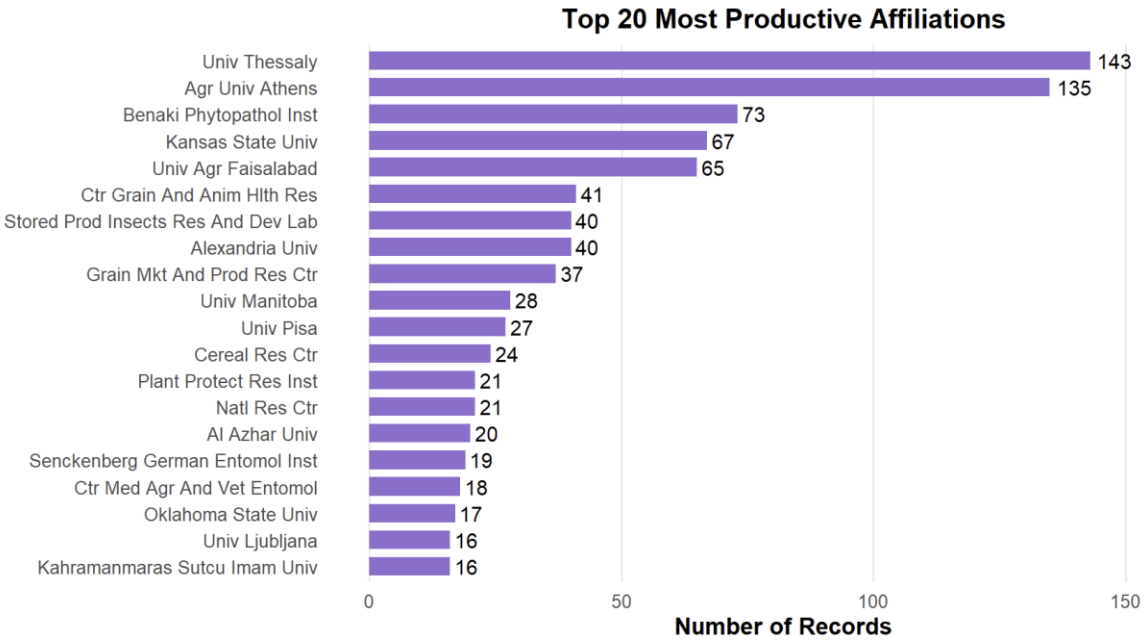
En üretken yazarlar ve kurumlara ilişkin bulgular, literatürün belirli araştırmacılar ve araştırma merkezleri etrafında yoğunlaştığını göstermektedir. Athanassiou CG, Kavallieratos NG ve Arthur FH'nin en üretken yazarlar olarak öne çıkması; University of Thessaly, Agricultural University of Athens ve Benaki Phytopathological Institute gibi Yunanistan merkezli kurumların üst sıralarda yer almasıyla birlikte değerlendirildiğinde, alanın özellikle Yunanistan merkezli güçlü bir araştırma hattına sahip olduğu anlaşılmaktadır (Şekil 1, 2). Bu durum ülke dağılımı bulgularıyla da tutarlıdır. Yunanistan ve ABD'nin hem yayın üretiminde hem de iş birliği ağlarında merkezi konumda bulunması, bu ülkelerin yalnızca nicel üretim bakımından değil, bilgi dolaşımı ve ortak araştırma yapıları bakımından da belirleyici aktörler olduğunu göstermektedir. Bibliyometrik çalışmalarda ortak yazarlık ve ülke iş birliği

ağları, araştırma alanındaki bilgi üretiminin sosyal ve kurumsal örgütlenmesini görünür kılan önemli göstergeler olarak değerlendirilmektedir (Zupic & Čater, 2015).



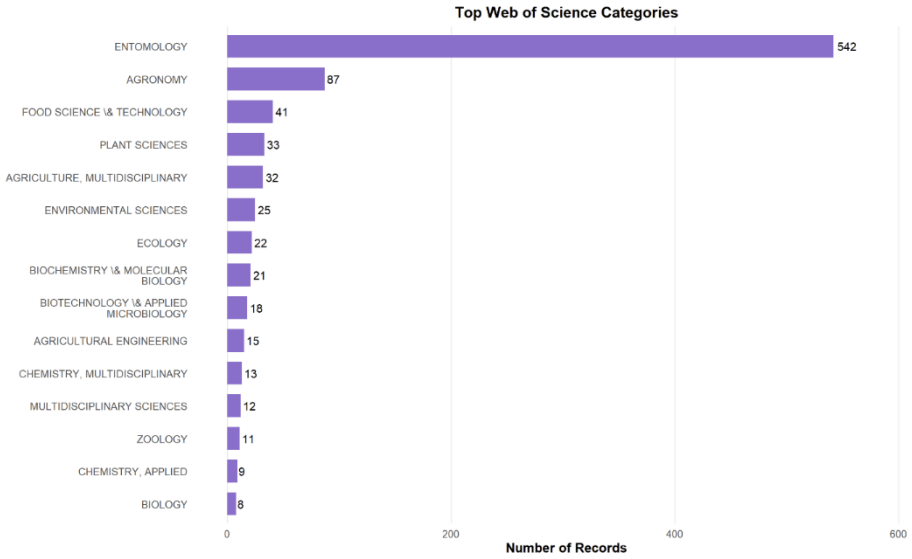
Şekil 2. Yazar Adreslerine Dayalı Ülke/Bölge Dağılımı

Yazar adreslerine göre en üretken kurumlar Şekil 3'te verilmiştir. Bulgulara göre University of Thessaly 143 kayıtla ilk sırada yer alırken, onu Agricultural University of Athens 135 kayıtla ve Benaki Phytopathological Institute 73 kayıtla izlemiştir. İlk üç kurumun Yunanistan merkezli olması, ülke dağılımında Yunanistan'ın ilk sırada yer almasıyla tutarlıdır. Ayrıca Kansas State University, University of Agriculture Faisalabad, Alexandria University ve University of Manitoba gibi kurumların da alana önemli katkı sunduğu görülmektedir. Türkiye'den Kahramanmaraş Sütçü İmam University 16 kayıtla ilk 20 kurum arasında yer almıştır.



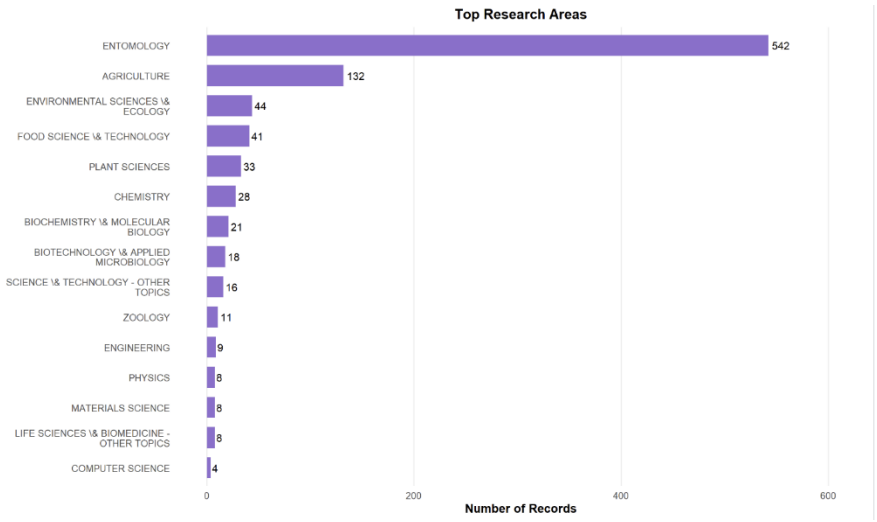
Şekil 3. Yazar Adreslerine Göre En Üretken Kurumlar

Yayınların Web of Science kategorilerine göre dağılımını ise Şekil 4'te gösterilmiştir. Entomology 542 kayıtla ilk sırada yer alırken, bunu 87 kayıtla Agronomy, 41 kayıtla Food Science & Technology, 33 kayıtla Plant Sciences ve 32 kayıtla Agriculture, Multidisciplinary kategorileri izlemiştir. Entomology kategorisinin açık biçimde ilk sırada yer alması beklenen bir sonuçtur; çünkü *S. oryzae* öncelikle depolanmış ürün entomolojisi kapsamında ele alınan bir zararlıdır. Bununla birlikte Agronomy, Food Science & Technology, Plant Sciences, Agriculture ve Environmental Sciences & Ecology alanlarının da görünür olması, konunun tek disiplinli bir çerçeveyle sınırlı olmadığını göstermektedir. Depolanmış buğdayda zararlı yönetimi; ürün kalitesi, gıda güvenliği, çevresel etki, kalıntı riski ve sürdürülebilir tarım uygulamalarıyla doğrudan ilişkilidir. Bu nedenle alanın entomoloji merkezli fakat tarım, gıda bilimi ve çevre bilimleriyle bağlantılı disiplinler arası bir yapı sergilemesi beklenen ve anlamlı bir bulgudur.



Şekil 4. Yayınların Web of Science Kategorilerine Göre Dağılımı

Şekil 5, yayınların araştırma alanlarına göre dağılımını göstermektedir. Bulgular, literatürün büyük ölçüde Entomoloji alanında yoğunlaştığını göstermektedir. Entomology 542 kayıtla ilk sırada yer alırken, bunu Agriculture 132 kayıtla, Environmental Sciences & Ecology 44 kayıtla, Food Science & Technology 41 kayıtla ve Plant Sciences 33 kayıtla izlemiştir. Bu dağılım, pirinç biti ve buğday ilişkili çalışmaların temel olarak entomoloji ve tarım bilimleri alanlarında konumlandığını; bununla birlikte çevre bilimleri, gıda bilimi ve bitki bilimleriyle de ilişkili olduğunu göstermektedir.

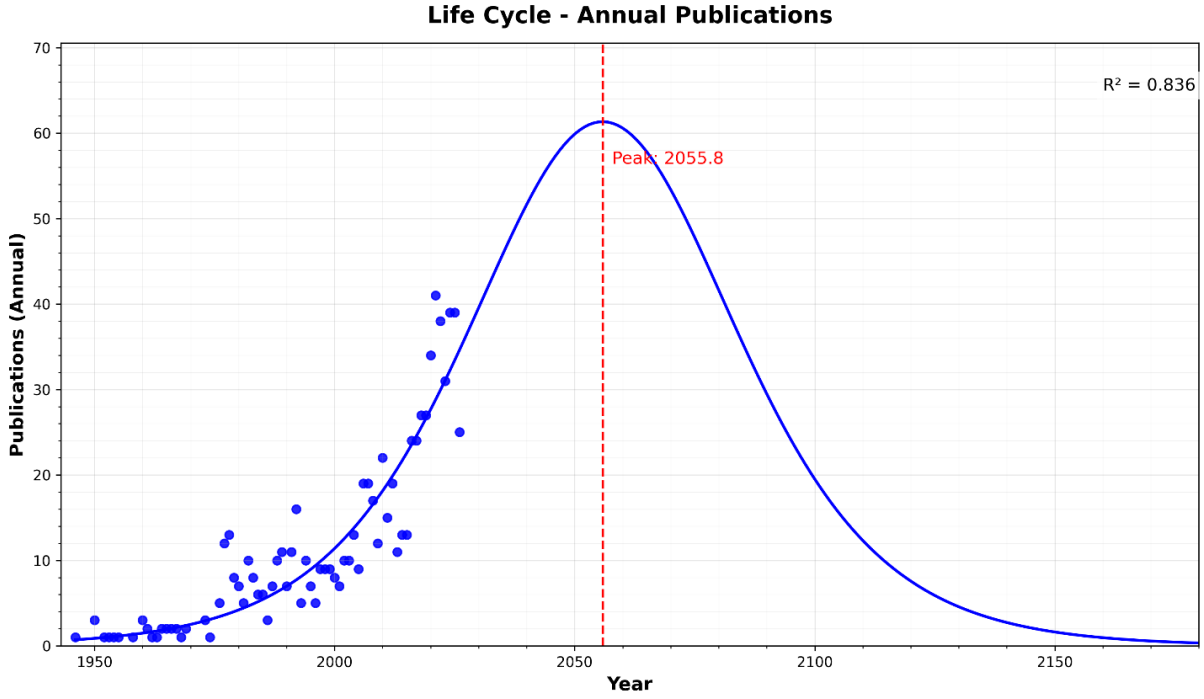


Şekil 5. Yayınların Araştırma Alanlarına Göre Dağılımı

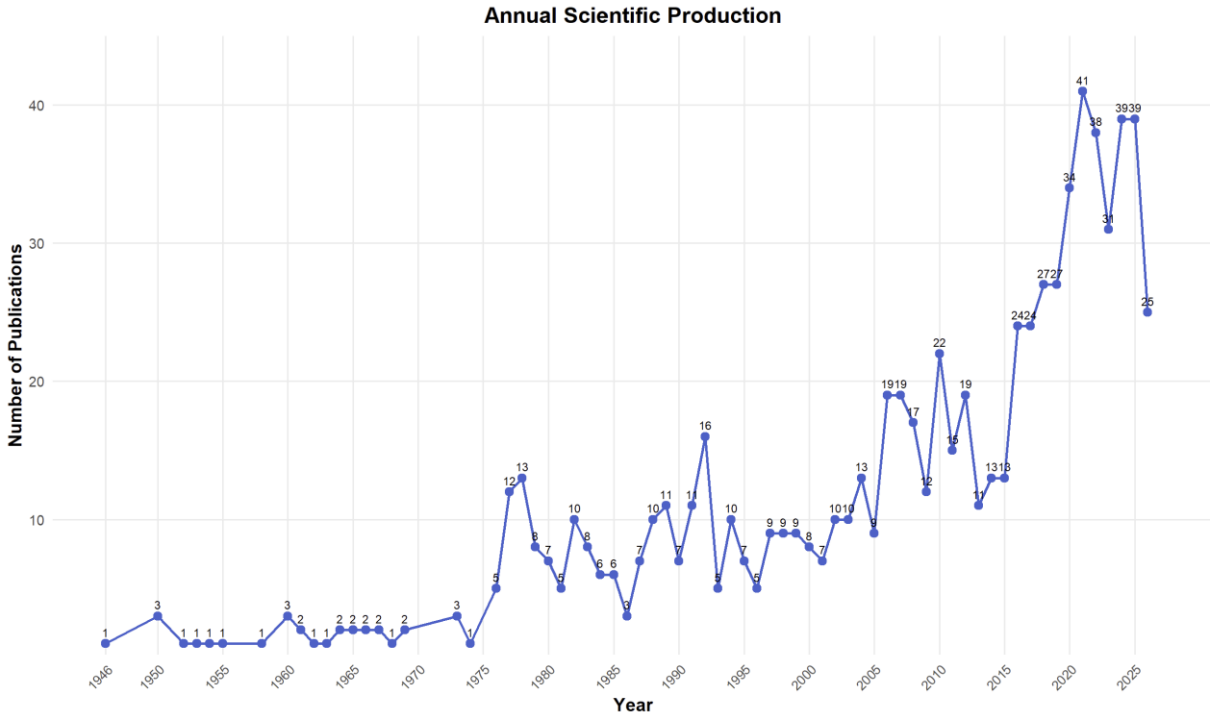
1946 ile 2026 yılları arasındaki gözlemlenen yıllık yayın sayıları ve lojistik büyüme modelinin türevine dayalı tahmini yaşam döngüsü eğrisi Şekil 6'da verilmiştir. Modele göre yıllık yayın üretiminin tepe noktasına yaklaşık 2055.8 yılında ulaşacağı ve bu dönemde yıllık yayın sayısının yaklaşık 61.3 olacağı tahmin edilmektedir. Gözlenen yayınların eğrinin yükselen kısmında yoğunlaşması, alanın henüz yayın doygunluğuna ulaşmadığını ve hâlen büyüme evresinde olduğunu göstermektedir. Modelin uyum düzeyi ise $R^2 = 0.836$ olarak hesaplanmıştır.

Lojistik yaşam döngüsü analizinde yayın üretiminin tepe noktasına gelecekte ulaşacağının tahmin edilmesi, bu literatürün araştırma potansiyelinin devam ettiğini düşündürmektedir. Ancak bu bulgunun model temelli bir kestirim olduğu unutulmamalıdır. Bibliyometrik yaşam döngüsü analizleri, geçmiş yayın eğilimlerinden hareketle alanın gelişim yönünü değerlendirmeye imkân verse de gelecekteki yayın üretimi; iklim değişikliği, gıda güvenliği politikaları, depolama teknolojilerindeki gelişmeler, insektisit direnci ve alternatif mücadele yöntemlerine yönelik araştırma fonları gibi çok sayıda dış etkene bağlı olarak değişebilir. Bu nedenle model sonucunun kesin bir öngörüden çok, alanın mevcut büyüme eğilimini yansıtan analitik bir gösterge olarak yorumlanması daha uygundur.

Şekil 7'de ise, 1946-2026 yılları arasında pirinç biti ve buğday ilişkili araştırmalara ait yıllık yayın sayılarını göstermektedir. Bulgular, 1946-1970'li yıllar arasında yayın üretiminin oldukça sınırlı kaldığını, 1970'lerin ikinci yarısından itibaren dalgalı bir artış başladığını göstermektedir. 2000'li yıllardan sonra yayın sayılarında daha belirgin bir yükseliş görülmüş, özellikle 2015 sonrası dönemde yayın üretimi hızlanmıştır. En yüksek yayın sayısına 2021 yılında 41 yayınla ulaşılmıştır. Yayın üretiminin özellikle 2015 sonrasında belirgin biçimde hızlanması, depolanmış tahıl zararlıları konusunun son dönemde daha fazla bilimsel ilgi gördüğüne işaret etmektedir. Bu artış, gıda güvenliği, hasat sonrası kayıpların azaltılması, fumigant direnci ve çevre dostu zararlı yönetimi arayışlarının tarımsal araştırmalarda giderek daha görünür hâle gelmesiyle açıklanabilir. Nitekim *S. oryzae*, depolanmış tahıllarda nicel ve nitel kayıplara yol açan önemli zararlılardan biri olarak tanımlanmakta; bu zararlının buğday, arpa, mısır ve sorgum gibi farklı ürünlerde ekonomik kayıplara neden olduğu vurgulanmaktadır (Kandel et al., 2021).

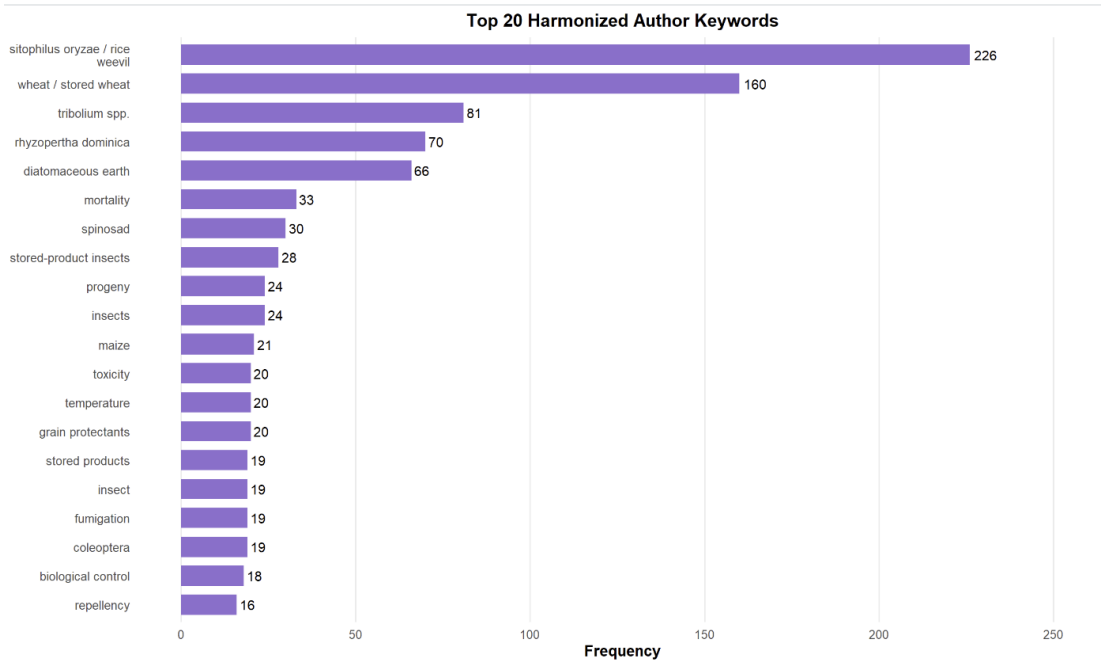


Şekil 6. Yıllık Yayın Üretiminin Yaşam Döngüsü Analizi



Şekil 7. Yıllara Göre Bilimsel Yayın Üretimi

Birleştirilmiş yazar anahtar kelimelerine göre en sık kullanılan 20 anahtar kelime ise Şekil 8'de verilmiştir. Eş anlamlı veya yakın anlamlı terimlerin birleştirilmesinden sonra *S. oryzae* / rice weevil en sık kullanılan anahtar kelime grubu olarak öne çıkmıştır (n = 226). Bunu wheat / stored wheat (n = 160), *Tribolium* spp. (n = 81), *Rhyzopertha dominica* (n = 70) ve diatomaceous earth (n = 66) izlemiştir. Mortality, spinosad, stored-product insects, toxicity, temperature, grain protectants, fumigation, biological control ve repellency gibi terimlerin öne çıkması, literatürün depo zararlıları yönetimi ve kontrol stratejileri etrafında yoğunlaştığını göstermektedir.

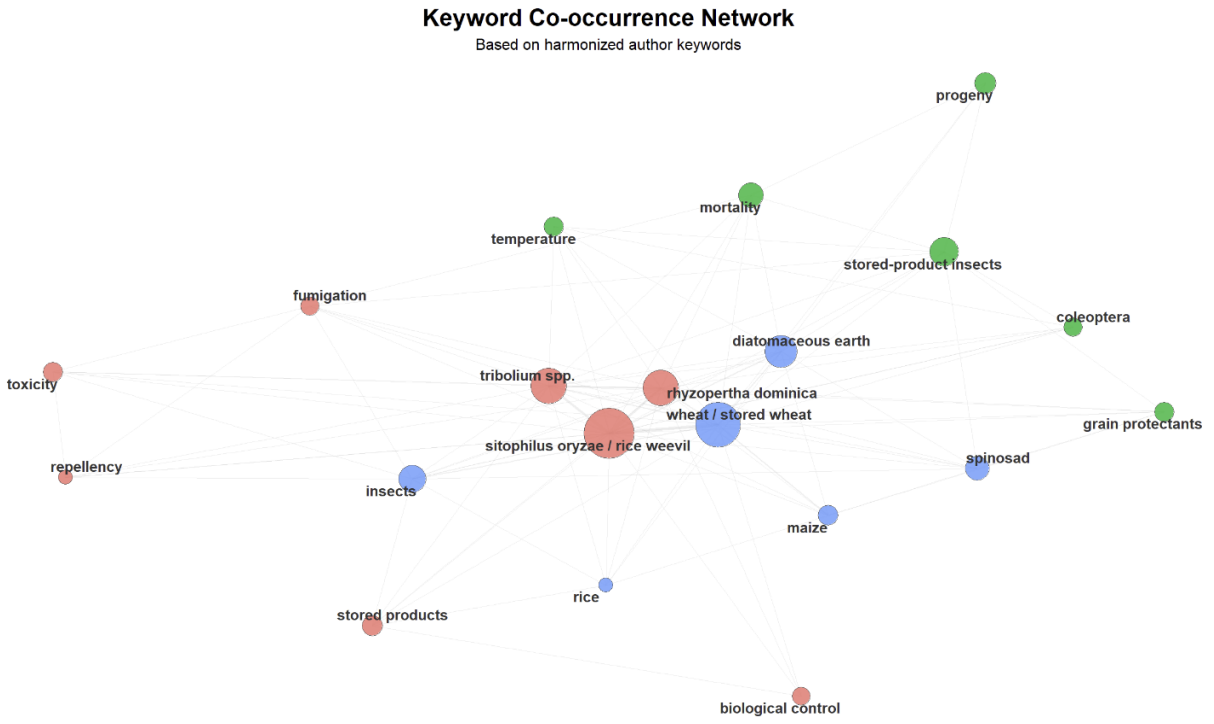


Şekil 8. Birleştirilmiş Yazar Anahtar Kelimelerine Göre En Sık Kullanılan 20 Anahtar Kelime

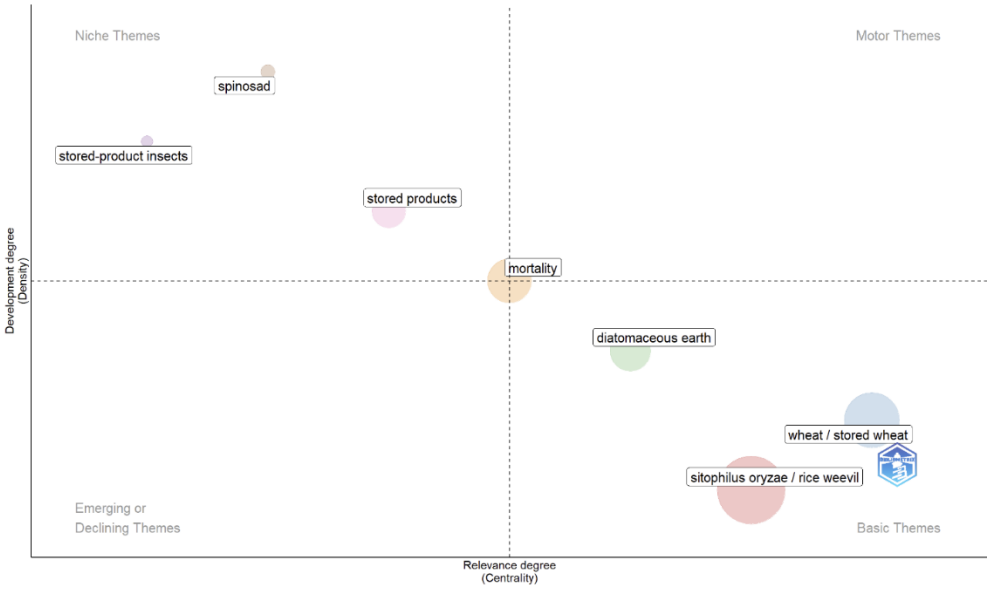
Birleştirilmiş yazar anahtar kelimelerine dayalı anahtar kelime birlikte-görünüm ağı ise Şekil 9'da verilmiştir. Ağda *S. oryzae* / rice weevil, wheat / stored wheat, *Tribolium* spp., *Rhyzopertha dominica* ve diatomaceous earth düğümlerinin merkezi konumda olduğu görülmektedir. Bu yapı, literatürün temel olarak depo zararlıları, buğdayın depolanması ve zararlı kontrol stratejileri etrafında şekillendiğini göstermektedir. Ayrıca mortality, temperature, toxicity, spinosad, fumigation, grain protectants, biological control ve repellency gibi anahtar kelimelerin ağda yer alması, çalışmaların zararlıların yaşama oranı, insektisit etkinliği ve alternatif mücadele yaklaşımlarına odaklandığını ortaya koymaktadır. Bu bulgu, depolanmış ürün zararlıları literatüründe kimyasal mücadeleden alternatif ve bütünleşik mücadele yaklaşımlarına doğru genişleyen araştırma yönelimiyle uyumludur (Hagstrum et al., 2012; Phillips & Throne, 2010).

Şekil 10, birleştirilmiş yazar anahtar kelimelerine dayalı tematik haritayı göstermektedir. Harita, alanın kavramsal yapısının büyük ölçüde *S. oryzae* / rice weevil, wheat / stored wheat ve diatomaceous earth temel temaları etrafında şekillendiğini göstermektedir. Diyatom toprağının merkezi temalardan biri hâline gelmesi, fosfin ve diğer kimyasal uygulamalara yönelik direnç, kalıntı ve çevresel risk tartışmalarıyla ilişkilidir. Diyatom toprağı, böcek kutikulasındaki mumsu tabakayı aşındırarak dehidrasyona neden olan fiziksel etki mekanizması nedeniyle doğal ve düşük kalıntı riski taşıyan bir mücadele seçeneği olarak ele alınmaktadır (Korunić, 1998). Ancak bu yöntemin etkinliği sıcaklık, bağıl nem, tane nemi, uygulama dozu ve zararlı türüne göre değişebilmektedir (Fields & Korunić, 2000; Yılmaz Doğu & Emekci, 2026). Dolayısıyla diyatom toprağına ilişkin çalışmaların yüksek görünürlüğü, alanın çevre dostu ve sürdürülebilir zararlı yönetimi arayışlarına yöneldiğini göstermektedir.

Buna karşılık spinosad, stored-product insects ve stored products niş temalar olarak öne çıkmakta; bu da daha uzmanlaşmış fakat kendi içinde gelişmiş araştırma alanlarına işaret etmektedir. Mortality anahtar kelimesi ise haritanın merkezine yakın konumuyla, tek başına özelleşmiş bir küme oluşturmaktan çok farklı tematik alanlar arasında bağ kuran bir kavram olarak değerlendirilebilir. Genel olarak tematik harita, literatürün depo zararlıları, buğday depolama bağlamı ve zararlı kontrol stratejileri etrafında yapılandığını ortaya koymaktadır.

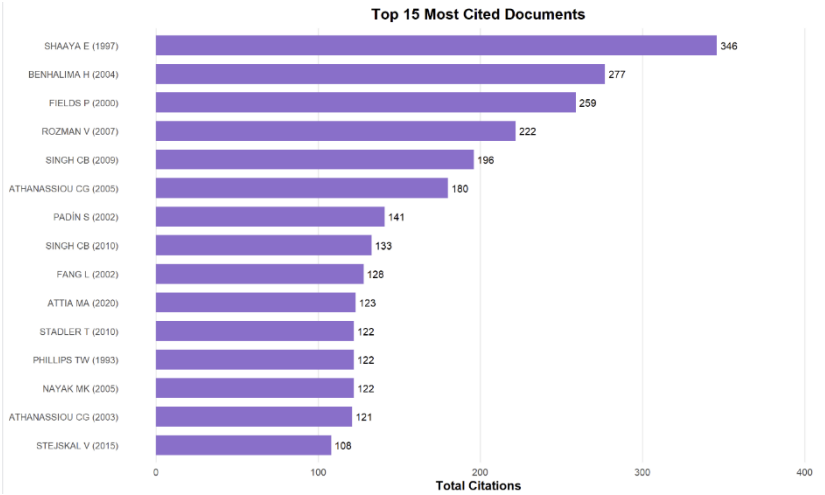


Şekil 9. Birleştirilmiş Yazar Anahtar Kelimelerine Dayalı Anahtar Kelime Birlikte-Görünüm Ağı



Şekil 10. Birleştirilmiş Yazar Anahtar Kelimelerine Dayalı Tematik Harita

En çok atıf alan yayınlara ilişkin bulgular (Şekil 11), literatürde etkili çalışmaların bitkisel yağlar, fosfin direnci, diyatom toprağı, spinosad ve zararlı tespiti gibi konular etrafında yoğunlaştığını göstermektedir. Shaaya ve arkadaşlarının (1997) bitkisel yağların fumigant ve temas etkilerine ilişkin çalışmasının en yüksek atıf (346) alan yayın olması, bitkisel kökenli bileşiklerin depolanmış ürün zararlılarıyla mücadelede uzun süredir ilgi gören bir alternatif olduğunu göstermektedir. Benhalima ve arkadaşlarının (2004) fosfin direnci üzerine çalışmasının yüksek atıf (277) alması ise fumigant direncinin alan için temel sorunlardan biri olduğunu ortaya koymaktadır. Fosfin direncinin küresel ölçekte artması, depolanmış ürün zararlılarıyla mücadelede mevcut uygulamaların sürdürülebilirliğini tehdit eden önemli bir gelişme olarak değerlendirilmektedir (Nayak et al., 2020). Bu bağlamda yüksek atıf alan yayınların tematik dağılımı, alanın yalnızca zararlının biyolojisine değil, etkili, güvenli ve sürdürülebilir kontrol stratejilerine odaklandığını göstermektedir. En çok atıf alan yayınların önemli bir bölümünün Journal of Stored Products Research dergisinde yayımlanmış olması, bu derginin depo zararlıları ve buğday depolama alanındaki etkili çalışmalar için merkezi bir kaynak olduğunu göstermektedir.

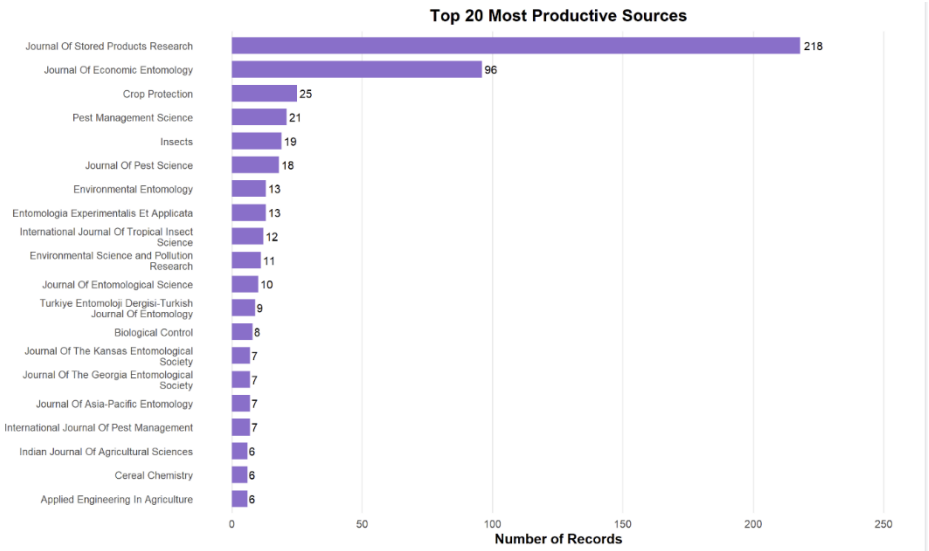


Şekil 11. Web Of Science Toplam Atıf Sayılarına Göre En Çok Atıf Alan 15 Yayın

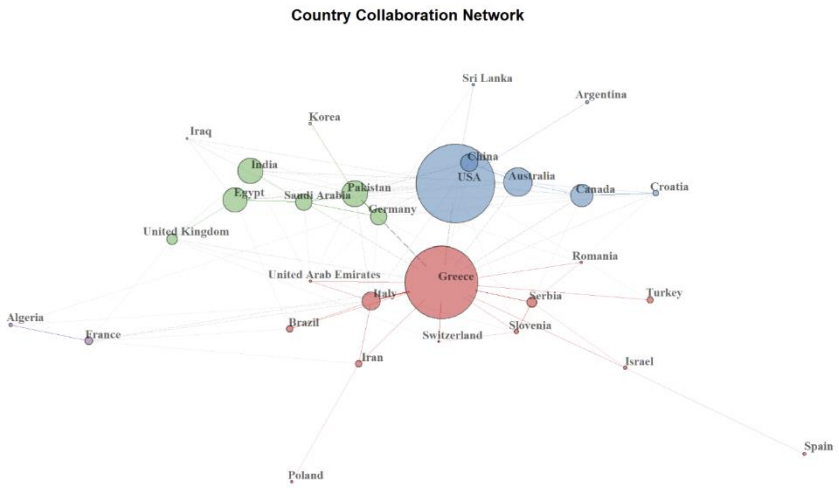
Şekil 12, incelenen literatürde en fazla yayın yayımlayan 20 kaynak/dergiyi göstermektedir. Bulgulara göre Journal of Stored Products Research, 218 kayıtla açık ara en üretken kaynak olarak öne çıkmıştır. Bu dergiyi, 96 kayıtla Journal of Economic Entomology, 25 kayıtla Crop Protection, 21 kayıtla Pest

Management Science ve 19 kayıtla Insects izlemiştir. Bu dağılım, pirinç biti ve buğday ilişkili çalışmaların özellikle depo ürünleri, entomoloji, zararlı yönetimi ve bitki koruma odaklı dergilerde yoğunlaştığını göstermektedir. Ayrıca Journal of Stored Products Research dergisinin yüksek yayın üretimi, bu alan için merkezi bir yayın platformu olduğunu ortaya koymaktadır.

Yazar adreslerinden elde edilen ülke bilgilerine dayalı olarak ülkeler arasındaki ortak yayın ilişkileri ise Şekil 13'te verilmiştir. Ağda ABD ve Yunanistan en büyük ve en merkezi düğümler olarak öne çıkmaktadır. Bu durum, söz konusu iki ülkenin hem yayın üretimi hem de uluslararası iş birlikleri bakımından alanda güçlü bir konuma sahip olduğunu göstermektedir. Avusturalya, Kanada, Çin, Pakistan, Hindistan, Mısır, Sudi Arabistan ve Almanya gibi ülkeler de ağ içinde belirgin bağlantılara sahiptir. Türkiye, ülke üretkenliği analizinde 45 kayıtla ilk 20 ülke arasında yer almasına rağmen, iş birliği ağında daha çevresel bir konumda görünmektedir. Bu bulgu, Türkiye'nin alana görünür bir yayın katkısı sunduğunu; ancak uluslararası ortak yayın ağındaki merkeziliğinin ABD ve Yunanistan gibi öncü ülkeler kadar güçlü olmadığını göstermektedir. Genel olarak ağ yapısı, alanın birkaç merkezi ülke etrafında yoğunlaşan, ancak farklı bölgelerden ülkelerin de dâhil olduğu uluslararası bir iş birliği örüntüsüne sahip olduğunu ortaya koymaktadır.

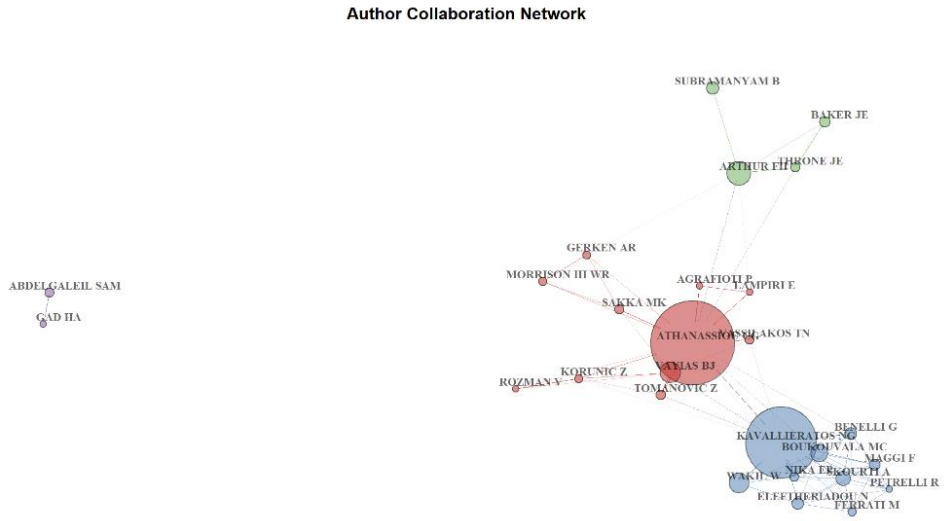


Şekil 12. En Üretken Kaynaklar/Dergiler



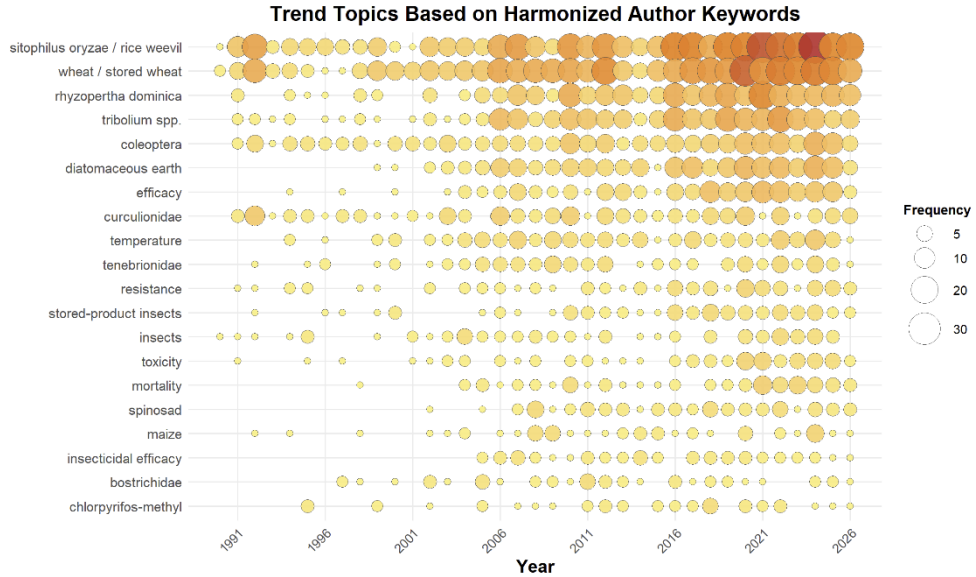
Şekil 13. Ülke İş Birliği Ağı

Yazar iş birliği ağı, alandaki ortak yazarlık ilişkilerini göstermektedir (Şekil 14). Düğümler yazarları, düğüm büyüklüğü yazarın ağ içindeki göreli ağırlığını/üretkenliğini, çizgiler ise yazarlar arasındaki iş birliği bağlantılarını temsil etmektedir. Ağ yapısı, özellikle Athanassiou CG ve Kavallieratos NG etrafında yoğunlaşan iş birliği kümelerinin öne çıktığını göstermektedir. Ayrıca Arthur FH'nin de ayrı bir iş birliği kümesinde önemli bir konuma sahip olduğu görülmektedir. Bulgular, alan yazında iş birliklerinin belirli çekirdek araştırmacılar etrafında kümelendiğini ve ortak yazarlık yapısının sınırlı sayıda güçlü araştırma grubu tarafından şekillendirildiğini ortaya koymaktadır.



Şekil 14. Yazar İş Birliği Ağı

Şekil 15 harmonize edilmiş yazar anahtar kelimelerine dayalı olarak yıllara göre öne çıkan trend konuları göstermektedir. Balonların büyüklüğü ve renk yoğunluğu, ilgili yıldaki anahtar kelime frekansını temsil etmektedir. Bulgular, *S. oryzae* / rice weevil ve wheat / stored wheat terimlerinin alanın süreklilik gösteren temel temaları olduğunu göstermektedir. Bunun yanında *Rhyzopertha dominica*, *Tribolium* spp., Coleoptera, diatomaceous earth, temperature, resistance, mortality, toxicity ve spinosad gibi anahtar kelimelerin özellikle 2000'li yıllardan sonra daha görünür hale geldiği görülmektedir. Bu durum, literatürün depo zararlıları, buğday depolama koşulları, zararlı türleri ve zararlı kontrol stratejileri etrafında geliştiğini ortaya koymaktadır.



Şekil 15. Yıllara Göre Öne Çıkan Anahtar Kelime Eğilimleri

SONUÇ

Bu araştırma, pirinç biti ve buğday ilişkili bilimsel literatürün üretim yapısını, kavramsal gelişimini, atıf örüntülerini ve iş birliği ağlarını bibliyometrik açıdan ortaya koymuştur. Bulgular, alanın uzun bir tarihsel geçmişe sahip olmakla birlikte özellikle 2000'li yıllardan sonra daha görünür hâle geldiğini, 2015 sonrası dönemde ise yayın üretiminin belirgin biçimde hızlandığını göstermektedir. Yaşam döngüsü analizi de alanın henüz doygunluğa ulaşmadığını ve büyüme evresini sürdürdüğünü ortaya koymuştur. Araştırma sonuçları, literatürün temel olarak entomoloji alanında yoğunlaştığını; ancak agronomi, gıda bilimi, bitki bilimleri, çevre bilimleri ve tarımsal araştırmalarla da ilişkili disiplinler arası bir yapıya sahip olduğunu göstermektedir. En üretken yazarlar arasında Athanassiou CG, Kavallieratos NG ve Arthur FH öne çıkarken, Yunanistan ve ABD alanın en görünür ve en merkezi ülkeleri olarak belirlenmiştir. Kurumsal düzeyde University of Thessaly, Agricultural University of Athens ve Benaki Phytopathological Institute'un öne çıkması, alanın özellikle Yunanistan merkezli güçlü bir araştırma hattına sahip olduğunu göstermektedir. Kavramsal ve tematik bulgular, literatürün *S. oryzae*, buğday, depo zararlıları, *Tribolium* türleri, *Rhyzopertha dominica*, diyatom toprağı, mortalite, toksisite, sıcaklık, fumigasyon, spinosad ve direnç gibi temalar etrafında şekillendiğini ortaya koymuştur. En çok atıf alan çalışmaların bitkisel yağlar, fosfin direnci, diyatom toprağı, spinosad ve zararlı tespiti gibi konularda yoğunlaşması, alanın yalnızca zararlının biyolojisine değil, aynı zamanda etkili, sürdürülebilir ve çevre dostu kontrol stratejilerine yöneldiğini göstermektedir. Dergi dağılımı açısından Journal of Stored Products Research, hem yayın sayısı hem de yüksek atıflı çalışmalar bakımından alanın temel yayın platformu olarak öne çıkmıştır. Bu durum, depolanmış ürün zararlıları ve buğday depolama araştırmalarının belirli bir çekirdek dergi etrafında yoğunlaştığını göstermektedir. Ülke ve yazar iş birliği ağları ise alanın birkaç güçlü araştırma grubu ve merkezi ülke etrafında yapılandığını ortaya koymuştur. Türkiye, 45 kayıtla ilk 20 ülke arasında yer alarak alana görünür bir katkı sunmuştur. Bununla birlikte Türkiye'nin uluslararası iş birliği ağında daha çevresel bir konumda kalması, yayın üretiminin uluslararası ortaklıklarla daha fazla desteklenmesi gerektiğini göstermektedir. Bu doğrultuda Türkiye merkezli araştırmaların özellikle direnç izleme, alternatif mücadele yöntemleri, diyatom toprağı, çevre dostu kontrol stratejileri ve karşılaştırmalı saha çalışmaları alanlarında uluslararası ortaklıklarını artırması önerilmektedir. Genel olarak bu araştırma pirinç biti ve buğday ilişkili literatürün büyüyen, entomoloji merkezli fakat disiplinler arası niteliği güçlü bir araştırma alanı olduğunu ortaya koymaktadır. Alanın gelecekte sürdürülebilir depolama uygulamaları, kimyasal olmayan kontrol yöntemleri, erken tespit teknolojileri ve uluslararası araştırma ağları ekseninde gelişmeye devam edeceği öngörülmektedir.

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ELLİ YILLIK MAKARNA ARAŞTIRMALARI: BİBLİYOMETRİK BİR PERSPEKTİF

FIVE DECADES OF PASTA RESEARCH: A BIBLIOMETRIC PERSPECTIVE

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ÖZET

Bu çalışmada, Web of Science (WoS) veri tabanında 1976-2026 yılları arasında indekslenen makarna konulu bilimsel yayınların bibliyometrik analizi gerçekleştirilerek, alandaki bilimsel gelişimin ve araştırma eğilimlerinin ortaya konulması amaçlanmıştır. Bibliyometrik analiz sonucunda, 779 farklı kaynakta yayımlanmış toplam 2.825 belge belirlenmiş ve yıllık bilimsel üretim artış oranının %10,4 olduğu tespit edilmiştir. Belge başına ortalama atıf sayısı 23,4, ortalama belge yaşı ise 11,4 yıl olarak belirlenmiştir. Literatüre toplam 8.911 yazar katkıda bulunmuş ve belge başına ortalama ortak yazar sayısı 4,8 olarak hesaplanmıştır. Yayınların %22,7'inde uluslararası ortak yazarlık bulunması, alandaki araştırmaların önemli ölçüde uluslararası iş birliği ile yürütüldüğünü göstermektedir. Veri setinde 5.823 yazar anahtar kelimesi ve 4.343 Keywords Plus terimi belirlenmiş olup, bu durum makarna araştırmalarının geniş ve çok yönlü bir konu alanına sahip olduğunu ortaya koymaktadır. Genel olarak bulgular, makarna araştırmalarının son beş on yılda istikrarlı biçimde büyüyen, yüksek düzeyde iş birliğine dayalı ve geniş bir bilimsel kapsama sahip bir araştırma alanı olduğunu göstermektedir. Elde edilen bibliyometrik profil, bu alandaki bilimsel gelişimin genel görünümünü sunmakta ve başlıca araştırma eğilimleri ile yeni ortaya çıkan konuların belirlenmesine temel oluşturmaktadır.
Anahtar kelimeler: Makarna, bilimsel üretim, araştırma eğilimleri

ABSTRACT

This study aimed to evaluate the global research landscape and scientific trends in pasta / macaroni research through a bibliometric analysis of publications indexed in the Web of Science (WoS) database between 1976 and 2026. The bibliometric analysis identified 2,825 documents published across 779 sources, with an annual growth rate of 10.4%, indicating a substantial and continuing expansion of research activity in this field. The documents received an average of 23.4 citations per publication and had a mean document age of 11.4 years. A total of 8,911 authors contributed to the literature, with an average of 4.8 co-authors per document, while 22.7% of publications involved international co-authorship. The dataset included 5,823 authors' keywords and 4,343 Keywords Plus terms, reflecting a broad range of research topics associated with macaroni and pasta. Overall, the findings demonstrate a steadily growing and highly collaborative research field, with considerable scientific output and increasing international collaboration. The bibliometric profile provides an overview of the development and scope of research on macaroni and pasta over the past five decades and offers a basis for identifying major research trends and emerging topics in this field.
Keywords: Macaroni, scientific production, research trends

GİRİŞ

Makarnanın kökenine ilişkin farklı görüşler bulunmakla birlikte, genel kabul gören yaklaşım, bu ürünün belirli bir kişi veya kültür tarafından tek başına icat edilmediği ve yalnızca bir ulusa ait bir ürün olarak değerlendirilmemesi gerektiğidir. Aksine, makarna farklı coğrafyalarda ve uygarlıklarda zaman içerisinde gelişerek şekillenen çok katmanlı bir tarihsel sürecin ürünü olarak değerlendirilmektedir. Tarihsel kaynaklar, makarnaya veya makarna benzeri hamur ürünlerine ilişkin izlerin Etrüskler, Romalılar, Araplar ve Çinliler başta olmak üzere farklı uygarlıklarda bulunduğunu göstermektedir. Özellikle MS 960-1280 yılları arasında Çin'de makarnaya benzer ürünlerin tüketildiğine ilişkin kayıtlar bulunmakta ve bu ürünlerin Marco Polo'nun Çin seyahati sonrasında Avrupa'ya, özellikle İtalya'ya taşındığı yönünde yaygın bir görüş bulunmaktadır (Yargun, 2025). Makarna, Akdeniz diyetinin temel gıdalarından biri olup farklı yaş ve sosyoekonomik gruplardan insanlar tarafından yaygın olarak tüketilmektedir. Yaygın tüketiminde; uzun raf ömrü, uygun fiyatı, hazırlanmasının kolay ve pratik

olması, kullanım kolaylığı ve dünya genelinde kolaylıkla ulaşılabilir olması gibi çeşitli avantajları etkili olmaktadır (Taşcı ve ark., 2023).

Türkiye makarna sektörü, yüksek üretim kapasitesi ve ihracat potansiyeli ile ülke tarım ve gıda sanayisinin önemli sektörlerinden biridir. Ülkemizde toplam 2,8 milyon ton/yıl üretim kapasitesine sahip 26 makarna fabrikası faaliyet göstermekte; sektörde yaklaşık 10 bin kişi doğrudan, 100 bin kişi ise dolaylı olarak istihdam edilmektedir. Türkiye, makarna üretiminde dünya genelinde genellikle ikinci sırada yer almaktadır (TMSD, 2022; Taşcı ve ark., 2022). Nitekim, 2010 yılında yaklaşık 734.159 ton olan Türkiye'nin makarna üretimi, 2025 yılında 2.071.584 tona ulaşarak önemli bir artış göstermiştir (TÜİK, 2026).

Türkiye, makarna ihracatında da küresel ölçekte önemli bir konuma sahiptir. 2026 yılı verilerine göre Türkiye, yaklaşık 1,4 milyon tonluk makarna ihracatı ile 2,6 milyon ton ihracat gerçekleştiren İtalya'nın ardından dünya genelinde ikinci sırada yer almaktadır. Türkiye'de üretilen makarna, başta Afrika ve Asya ülkeleri olmak üzere 165 ülkeye ihraç edilmektedir. İhracatın gerçekleştirildiği başlıca ülkeler Gana (166 bin ton), Somali (162 bin ton), Togo (114 bin ton), Benin (102 bin ton) ve Japonya (75 bin ton) olup, diğer ülkeler de önemli bir pazar payına sahiptir (TradeMap, 2026). Bu veriler, Türkiye makarna sektörünün yalnızca üretim kapasitesi açısından değil, aynı zamanda uluslararası ticaretteki etkinliği ve geniş ihracat ağı bakımından da önemli bir konuma sahip olduğunu göstermektedir.

Makarna, günlük beslenmede yaygın olarak tüketilen temel gıda ürünlerinden biridir (Taşçı ve ark., 2023). Kişi başına yıllık makarna tüketimi açısından İtalya, 23,5 kg ile ilk sırada yer alırken, Tunus 17 kg ile ikinci, Türkiye ise 7,53 kg ile 14. sırada yer almaktadır (IPO, 2022). Türkiye'de makarna tüketiminin 14. sırada yer almasının başlıca nedenlerinden biri, makarnaya alternatif olarak tüketilen ve makarnalık buğdaydan üretilen ve geleneksel bir ürün olan bulgurun yaygın tüketimidir. Bununla birlikte, Türkiye'de makarna tüketimi her geçen yıl artış göstermektedir (Taçcı ve ark., 2023).

Türkiye, özellikle Güneydoğu Anadolu Bölgesi, topografik özellikleri, toprak yapısı ve sahip olduğu geleneksel tarım nedeniyle makarnanın temel hammaddesi olan makarnalık buğdayının yetiştirilmesi için uygun koşullara sahiptir. Makarna, *Triticum durum* buğdayının uygun koşullarda öğütülmesiyle elde edilen irmiğin su ile yoğrulması, farklı şekiller verilmesi ve kurutulmasıyla üretilen yarı hazır bir gıda ürünüdür (Muslu ve ark., 2021). Yapısında bulunan kompleks karbonhidratların hızlı bir şekilde enerjiye dönüştürülebilmesi, vitamin ve mineraller bakımından zengin olması ve yüksek enerji değerine sahip bulunması nedeniyle önemli bir besin kaynağı olarak değerlendirilmektedir (Demirkol ve İçöz, 2002).

Son yıllarda bibliyometrik teknikler, araştırma eğilimlerini ortaya koymak, bilgi boşluklarını belirlemek ve gelecekteki bilimsel ve politika önceliklerine yön vermek amacıyla tarım ve gıda bilimlerinde giderek daha fazla kullanılmaktadır (Giraldo ve ark., 2019). Bibliyometrik analiz; yazar ve kurum bilgileri, atıf sayıları ve anahtar kelime birliktelikleri gibi yayın üst verilerinden yararlanarak bilimsel araştırmaları, yayın çıktıları, atıf ağları ve iş birliği örüntüleri üzerinden nicel olarak değerlendiren bir yöntemdir (Aria ve Cuccurullo, 2017; Yuan ve Sun, 2022). Bu yaklaşım, belirli bir alandaki bilginin yapısı ve dinamikleri hakkında önemli bilgiler sunarak etkili yazar, kurum ve ülkelerin belirlenmesine; bilgi boşluklarının, yeni ortaya çıkan araştırma konularının ve gelecekteki araştırma yönelimlerinin ortaya konulmasına olanak sağlamaktadır (Liaqat ve ark., 2025).

Web of Science (WoS) Core Collection, dergilerin titiz seçim süreçlerinden geçirilmesi ve standartlaştırılmış indeksleme sistemi nedeniyle bibliyometrik araştırmalarda en güvenilir ve kapsamlı veri tabanlarından biri olarak kabul edilmektedir (Birkle ve ark., 2020). Bu çalışmanın amacı, 1976-2026 yılları arasında makarna konusunda yayımlanan bilimsel literatürü bibliyometrik açıdan analiz ederek araştırma eğilimlerini, öne çıkan araştırmacıları, kurumları, ülkeleri, dergileri ve tematik araştırma alanlarını ortaya koymaktır. Elde edilen bulguların, gelecekteki araştırma yönelimlerinin belirlenmesine katkı sağlamasının yanı sıra sürdürülebilir, verimli ve yüksek kaliteli makarna değer zincirlerinin geliştirilmesine yönelik bilimsel çalışmalara temel oluşturması hedeflenmektedir.

YÖNTEM

Bu çalışmada kullanılan bibliyometrik veriler; Science Citation Index (SCI) Expanded ve Emerging Sources Citation Index (ESCI) dizinlerini kapsayan WoS Core Collection'dan elde edilmiştir. WoS'un kökeni, Eugene Garfield tarafından kurulan Institute for Scientific Information'ın (Bilimsel Bilgi Enstitüsü) başlangıçta bir bilgi erişim aracı olarak Science Citation Index'i ticari kullanıma sunduğu 1964 yılına dayanmaktadır. SCI, Social Sciences Citation Index ve Arts & Humanities Citation Index

ile birleştirilerek 1997 yılında World Wide Web üzerinde Web of Science adıyla kullanıma sunulmuş ve platform günümüzde Clarivate Analytics tarafından işletilmektedir (Birkle ve ark., 2020). Makro düzeyde güvenilir bilimsel ölçüm (scientometric) veya bibliyometrik analizler sunmasıyla tanınan bu platform, köklü uygulamalara dayanan güçlü indeksleme standartlarına sahip olduğunu ortaya koymaktadır (Birkle ve ark., 2020; Raj ve Sahoo, 2024).

Bu araştırma kapsamındaki veriler, ilk olarak WOS veri tabanına girilerek çalışmaların başlığında "pasta" OR "macaroni" OR "spaghetti" anahtar kelimeleri kullanılarak, bu ifadelerden birini içeren çalışmalar 15.09.2026 tarihi itibarıyle araştırılmıştır. Bu arama sonucunda başlangıçta 3.666 kayıt elde edilmiştir. Bu kayıtlar daha sonra birbirini izleyen filtreleme aşamalarıyla daraltılmıştır. 2027 tarihli kayıtların (analiz 1976-2026 dönemini kapsamaktadır) hariç tutulmasıyla geriye 3.665 kayıt kalmıştır. Yalnızca araştırma makalelerini kapsayacak şekilde belge türüne göre yapılan filtreleme veri setini 2.947 kayda düşürmüştür. Aramanın İngilizce yazılmış makalelerle sınırlandırılması ise veri setini 2.825 kayda indirmiş ve nihai veri seti oluşturulmuştur. Elde edilen meta veriler BibTeX formatında dışa aktarılmış ve ardından R Studio yazılımında (version 4.4.2) Bibliometrix paketi Biblioshiny grafik arayüzü kullanılarak işlenmiştir (Aria ve Cuccurullo, 2017).

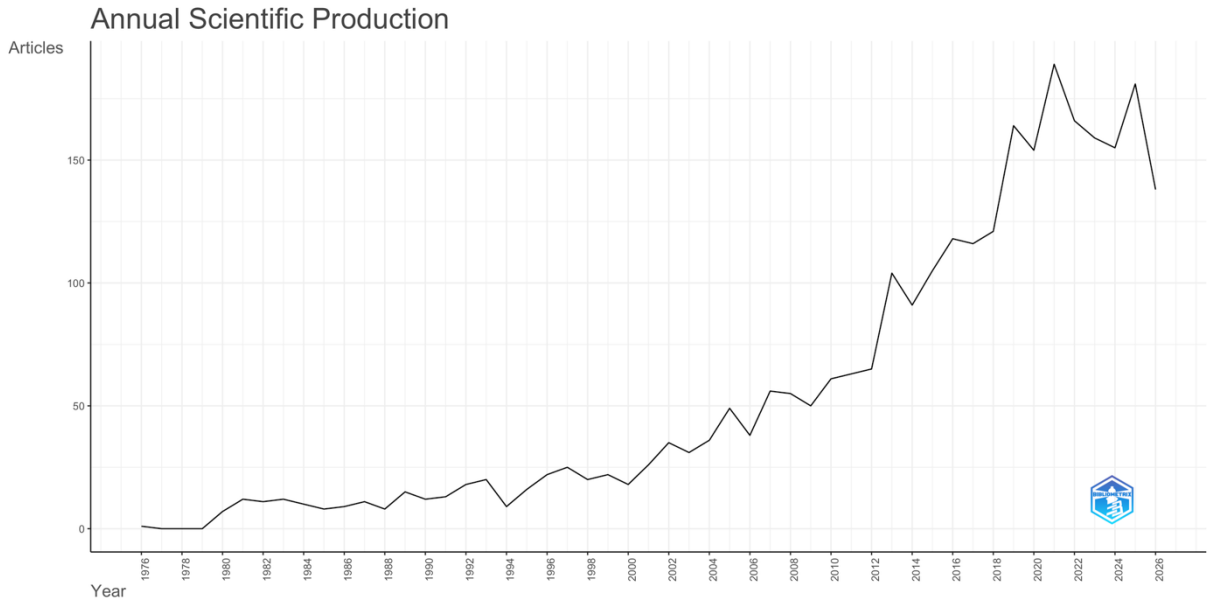
ARAŞTIRMA BULGULARI VE TARTIŞMA

Konu taraması sonucunda WoS veritabanından elde edilen makalelere yapılan tanımlayıcı analiz sonucunda belirlenen koleksiyona ait temel bilgiler Tablo 1'de verilmiştir.

Tablo 1. Koleksiyona Ait Tanımlayıcı Analiz

Veriler Hakkında Ana Bilgiler	
Zaman Aralığı	1976 : 2026
Kaynaklar (Dergi, Kitap vb.)	779
Makale Sayısı	2.825
Yıllık Büyüme Oranı (%)	10,4
Belgelerin Ortalama Yaşı	11,4
Belge Başına Ortalama Atıf	23,4
Referans Sayısı	65.105
Yazarlar	
Yazar	8.911
Tek Yazarlı Belge	163
Belge Başına Ortak Yazar	4,8
Uluslararası Ortak Yazarlıklar (%)	22,7

Web of Science veri tabanında bibliyometrik analizi sonucunda toplamda 2.825 adet araştırma makalesi elde edilmiştir (Tablo 1). Şekil 1'de makarna konusunda 1976-2026 yılları arasında gerçekleştirilen bilimsel çalışmaların yıllık değişimi verilmiştir. Grafik verileri incelendiğinde, konuyla ilgili yayın sayısının yıllar içinde genel olarak artan bir seyir izlediği görülmektedir. 1970'li ve 1980'li yıllarda yıllık çalışma sayısı oldukça düşük düzeylerde kalırken, özellikle 2010'lu yıllardan itibaren makarna ile ilgili akademik araştırmalarda çok hızlı bir artış yaşanmıştır. Çalışma sayısındaki en yüksek artış 2021 yılında gerçekleşmiş ve yıllık makale sayısı zirve noktasına ulaşmıştır. Son yıllarda gözlenen bu belirgin artış, makarnanın besinsel içeriğinin geliştirilmesi, zenginleştirilmiş/fonksiyonel makarna üretimi, glutensiz alternatifler ve yeni işleme teknolojileri gibi konulara olan akademik ve endüstriyel ilginin artmasıyla açıklanabilir. Benzer şekilde, Cecchini ve ark. (2020), makarnalık buğday ve makarna üzerine yaptıkları karşılaştırmalı bibliyometrik analizde, özellikle 2004 yılından itibaren yayın sayısında önemli bir artış olduğunu bildirmişlerdir; bu süreçte en erken çalışmalar genetik ve temel kalite özelliklerine odaklanırken, orta dönemdeki araştırmalar işleme, beslenme ve güvenliğe doğru genişlemiş, en güncel çalışmalar ise tüketici odaklı duyusal ve dokusal özelliklere yoğunlaşmıştır.



Şekil 1. Makarna ilgili olarak yapılan çalışmaların yıllık değişimi

Bu konuda yapılan çalışmaların yıllık büyüme oranı %10,4 olup, belgelerin ortalama yaşı ise 11,4'tür (Tablo 1). Çalışmada 172 WoS kategorisi, 110 çalışma alanı tespit edilmiştir. 1976-2026 yılları arasında yapılan çalışmaların WoS kategorilerine ve araştırma alanlarına göre ilk 20'si Tablo 2'de verilmiştir. Tablo 2 incelendiğinde, Food Science Technology'nin hem WoS kategorisinde hem de araştırma alanında 1497 makale ve %53'lük oranla ilk sırada yer aldığı görülmüştür. WoS kategorilerilerinde Chemistry Applied (%10,7) ve Nutrition Dietetics (%8,5); Araştırma Alanlarında ise Physics (%16,6) ve Chemistry (%14,4) öne çıkan başlıca disiplinler olmuştur. Elde edilen bu dağılım, makarna konusundaki akademik çalışmaların temel olarak ürün geliştirme, gıda kimyası ve besleyici değer üzerine yoğunlaştığını göstermektedir. Ayrıca Tarım, Kimya Mühendisliği, Biyokimya ve Biyoteknoloji gibi alanların da listede üst sıralarda yer alması, konunun tarladan sofraya uzanan zincirde disiplinlerarası bir yaklaşımla ele alındığını ortaya koymaktadır. Benzer şekilde Yuan ve Sun (2022), buğday araştırmalarının 78 WoS konu kategorisi ve 55 araştırma alanını kapsadığını tespit etmiştir. En öne çıkan kategori Plant Sciences olup, bunu Agronomy, Food Science & Technology, Multidisciplinary/General Science ve Environmental Sciences takip etmiştir. Araştırma alanlarında ise liderliği Plant Sciences ve Agriculture alırken, bunları Science & Technology - Other Topics, Environmental Sciences/Ecology ve Food Science & Technology izlemiştir.

Tablo 2. En iyi 20 WoS kategorisi ve araştırma alanı, 1976-2026

Sıra	WoS Kategorisi	Makale Sayısı	% Oranı	Araştırma Alanı	Makale Sayısı	% Oranı
1	Food Science Technology	1497	53,0	Food Science Technology	1497	53,0
2	Chemistry Applied	301	10,7	Physics	468	16,6
3	Nutrition Dietetics	240	8,5	Chemistry	408	14,4
4	Physics Mathematical	184	6,5	Nutrition Dietetics	240	8,5
5	Physics Multidisciplinary	145	5,1	Agriculture	195	6,9
6	Physics Fluids Plasmas	119	4,2	Engineering	139	4,9
7	Agriculture Multidisciplinary	99	3,5	Mathematics	116	4,1
8	Mathematics Applied	93	3,3	Biochemistry Molecular Biology	101	3,6
9	Biochemistry Molecular Biology	85	3,0	Environmental Sciences Ecology	88	3,1

10	Physics Nuclear	80	2,8	Science Technology Other Topics	88	3,1
11	Engineering Chemical	74	2,6	Biotechnology Applied Microbiology	58	2,1
12	Chemistry Multidisciplinary	72	2,5	Materials Science	53	1,9
13	Physics Applied	59	2,1	Mechanics	44	1,6
14	Biotechnology Applied Microbiology	58	2,1	Zoology	41	1,5
15	Agronomy	56	2,0	Microbiology	35	1,2
16	Multidisciplinary Sciences	54	1,9	Astronomy Astrophysics	29	1,0
17	Materials Science Multidisciplinary	49	1,7	Plant Sciences	28	1,0
18	Mechanics	44	1,6	Computer Science	27	1,0
19	Environmental Sciences	42	1,5	Toxicology	24	0,8
20	Ecology	40	1,4	Optics	23	0,8

Yayınlarda en çok kullanılan anahtar kelimelerin ağaç haritası (tree-map) analizi sonuçları Şekil 2'de sunulmuştur. Analiz sonuçlarına göre, literatürde en yüksek frekansa sahip olan temel kavramlar sırasıyla 'pasta' (%9), 'quality' (%8), 'spaghetti' (%5), 'starch' (%4), 'flour' (%4) ve 'cooking quality' (%4) olarak öne çıkmıştır. Tree-map haritasındaki kelime dağılımı incelendiğinde akademik odağın üç ana eksende yoğunlaştığı görülmektedir: İlk olarak, makarnanın tekstürel yapısı ve pişme özellikleri araştırmaların temel dayanağını oluşturmaktadır. İkinci olarak, fonksiyonel gıda geliştirme trendine paralel biçimde besinsel değerler (lif içeriği, antioksidan aktivite, sindirilebilirlik, glisemik indeks, polifenoller) ve glutensiz formülasyonlar sıklıkla çalışılan konular arasında yer almıştır. Son olarak, hammadde özellikleri ve proses teknolojileri kapsamında buğday, durum buğdayı, irmik, hamur reolojisi ve ekstrüzyon prosesi teknolojik açıdan yoğun incelenen parametreler olmuştur.



Şekil 2. Yayınlarda en çok rastlanan anahtar kelimelerin tree-map analizine ait görsel

Makarna ile ilgili olarak yapılan araştırma makalelerinin yayınlandığı dergilere bakıldığında, bu 2,825 araştırma makalesinin WoS veri tabanında taranan 779 farklı dergide yayınlandığı (Tablo 1), bu dergilerden 478 tanesinde sadece bir makale yayınlanırken, 301 dergide ise iki veya daha fazla makale yayınlandığı belirlenmiştir.
En fazla makalenin yayınlandığı dergi 128 makale ile Foods olurken, bunu LWT-Food Science and Technology (117), Food Chemistry (101), International Journal of Food Science and Technology (78), Physical Review E (77) ve diğer degiler takip etmiştir (Tablo 3).

Tablo 3. Makarna ile ilgili makalelerin yayınlandığı önemli dergiler

Kaynak	**Makale Sayısı**
Foods	128
LWT-Food Science and Technology	117
Food Chemistry	101
International Journal of Food Science and Technology	78
Physical Review E	77
Cereal Chemistry	74
Journal of Cereal Science	64
Physical Review C	59
Journal of Food Science	50
Journal of Food Processing and Preservation	45
Diğer Dergiler	2,032
Toplam	**2,825**

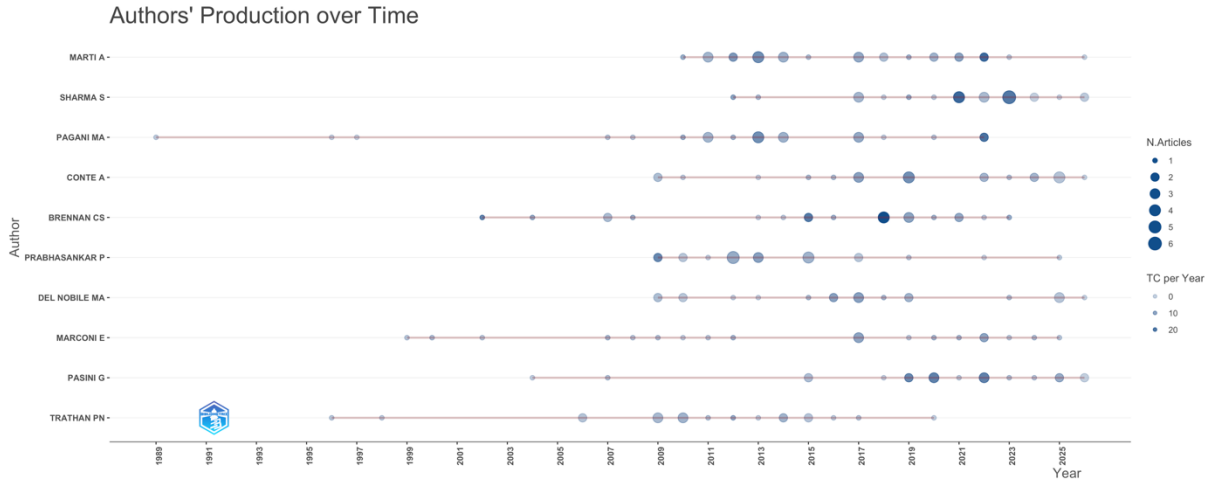
Bu çalışmaya konu olan makaleler incelendiğinde, ilk makalenin yayınlandığı 1976 yılından bu yana 163 tanesi tek isimli makale olmak üzere toplam 2.825 makalede 8.911 yazarın yer aldığı çalışma yayınlanmıştır. Makale başı yazar sayısı 4,8 olup, uluslararası iş birliği yapılan ortak yazarlı makale oranı %22,7 olmuştur (Tablo 1). Önceki çalışmalar, uluslararası iş birliğinin bilimsel çıktıların görünürlüğünü ve etkisini artırdığını göstermiştir (Donthu ve ark., 2021).
Makarna konusunda en fazla yayın üreten araştırmacılara ait veriler Tablo 4'te sunulmuştur. Veriler incelendiğinde, literatürde en yüksek makale sayısına sahip araştırmacının 28 yayın ile Marti A olduğu görülmektedir. Marti A'yı sırasıyla Sharma S (26 makale), Pagani Ma (24 makale), Conte A (23 makale), Brennan Cs (22 makale) ve Prabhasankar P (22 makale) izlemiştir.

Tablo 4. Makarna ile ilgili en fazla çalışması bulunan yazarlar

Yazar	**Makale Sayısı**	**Yazar**	**Makale Sayısı**
Marti A	28	Wojtowicz A	17
Sharma S	26	Bello-Perez La	16
Pagani Ma	24	Singh B	16
Conte A	23	Ponno A	15
Brennan Cs	22	Williams Td	15
Prabhasankar P	22	Fares C	14
Del Nobile Ma	20	İametti S	14
Marconi E	20	Micard V	14
Pasini G	20	Ruffo S	14
Trathan Pn	20	A. A	13
Manthey Fa	19	Carini E	13
Brennan Ma	18	Cimini A	13
Giuberti G	18	Horowitz Cj	13

Sobota A	18	Menezes Dp	13
Vittadini E	17	Simonato B	13

En üretken araştırmacıların zaman içindeki yayın performansları ve aldıkları atıf durumları Şekil 3'te verilmiştir. Grafikte yer alan dairelerin büyüklüğü ilgili yıldaki makale sayısını, rengin koyuluğu ise yıllık ortalama atıf sayısını göstermektedir. Bulgular incelendiğinde, Pagani MA'nın 1980'lerin sonundan günümüze kadar uzanan yayın geçmişiyle alandaki en kıdemli araştırmacılardan biri olduğu görülmektedir. Marti A ve Conte A gibi isimlerin özellikle 2010 sonrasında istikrarlı bir yayın çizgisine sahip oldukları göze çarpmaktadır. Etki boyutu (atıf oranı) açısından bakıldığında, Brennan CS'nin 2018 yılındaki yayınlarının ve Sharma S'nin 2021 ile 2023 yıllarındaki çalışmalarının yüksek atıf oranlarıyla öne çıktığı tespit edilmiştir. Araştırmacıların zamansal dağılımı, makarna alanındaki bilimsel üretimin 2010 yılından itibaren hem nitelik hem de nicelik yönünden ivme kazandığını doğrulamaktadır.



Şekil 3. Yazarların makarna ile ilgili çalışmalarının zaman içindeki üretimi

Bu 2.825 araştırma makalesi küresel olarak 66.062 atıf almış olup, makale başına ortalama atıf sayısı ise 23,4'tür (Tablo 1). Makarna ile ilgili yapılan makaleler atıf sayısına göre sıralandığı zaman; en fazla atıf 417 adet ile Tudorica CM'nin 2002 yılında yaptığı çalışmaya yapılmıştır. Bu çalışmayı, 401 adet atıf ile Walsh I (2014), 316 adet atıf ile Petittot M (2010), 316 adet atıf ile Mirarab S (2015), 285 adet atıf ile Ajila SM (2020) ve diğerleri takip etmiştir (Tablo 5).

Tablo 5. Makarna ile ilgili yapılan makalelerin aldığı küresel atıf sayısı

	Makale	**DOI**	**Küresel Atıf Sayısı**
1	Tudorica CM, 2002, J Agric Food Chem	10.1021/Jf0106953	417
2	Walsh I, 2014, Nucleic Acids Res	10.1093/Nar/Gku399	401
3	Petitot M, 2010, Food Res Int	10.1016/J.Foodres.2009.07.020	316
4	Mirarab S, 2015, J Comput Biol	10.1089/Cmb.2014.0156	316
5	Ajila CM, 2010, Innov Food Sci Emerg Technol	10.1016/J.İfset.2009.10.004	285
6	Zou W, 2015, Food Chem	10.1016/J.Foodchem.2015.05.032	240
7	Bourdon I, 1999, Am J Clin Nutr	-	236
8	Degidio MG, 1990, Cereal Chem	-	231
9	Prabhasankar P, 2009, Food Chem	10.1016/J.Foodchem.2008.12.047	228
10	Deagle BE, 2007, Plos One	10.1371/Journal.Pone.0000831	216

11	Livi R, 1985, Phys Rev A	10.1103/Physreva.31.1039	208
12	Trovato A, 2007, Protein Eng Des Sel	10.1093/Protein/Gzm042	206
13	Fradique M, 2010, J Sci Food Agric	10.1002/Jsfa.3999	204
14	Horowitz CJ, 2004, Phys Rev C	10.1103/Physrevc.69.045804	203
15	Yeats C, 2002, Trends Biochemsci	10.1016/S0968-0004(02)02164-3	199
16	Humphries JM, 2003, J Agric Food Chem	10.1021/Jf026073e	190
17	Maruyama T, 2005, Phys Rev C	10.1103/Physrevc.72.015802	189
18	Brennan CS, 2004, Food Chem	10.1016/J.Foodchem.2003.08.034	186
19	Cleary L, 2006, Int J Food Sci Technol	10.1111/J.1365-2621.2005.01141.X	183
20	Ovando-Martinez M, 2009, Food Chem	10.1016/J.Foodchem.2008.07.035	182

Bibliyometrik analiz sonucunda en çok atıf alan yazarlara ait bilgiler aşağıda verilmiştir (Tablo 6). Makarna alanında yapılan çalışmalarda en fazla atıf alan araştırmacılara ait veriler incelendiğinde, Marti A'nın 362 atıf ile listenin ilk sırasında yer aldığı görülmektedir. Marti A'yı sırasıyla Pagani MA (346 atıf), Brennan CS (326 atıf), Petitot M (255 atıf) ve Horowitz CJ (254 atıf) izlemektedir. Yazarların atıf sayılarına göre dağılımı, ilk sıralarda yer alan araştırmacıların çalışmalarının alandaki diğer bilim insanları tarafından sıklıkla referans gösterildiğini ve makarna literatürünün metodolojik ve teorik çerçevesinin şekillenmesinde bu kilit isimlerin belirleyici bir rol oynadığını ortaya koymaktadır.

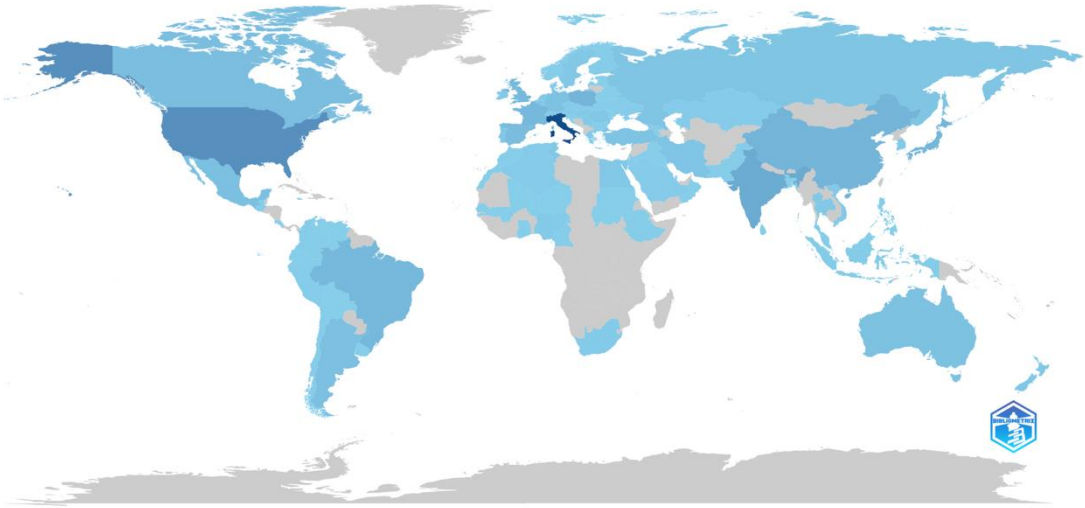
Tablo 6. En çok atıf alan 20 yazar sıralaması

Yazar	Atıf Sayısı	Yazar	Atıf Sayısı
Marti A	362	Marconi E	188
Pagani MA	346	Micard	184
Brennan CS	326	Valerıe V	184
Petitot M	255	Fares C	177
Horowitz CJ	254	Simonato B	171
Prabhasankar P	208	Barron C	168
Brennan MA	201	Bello-Perez LA	167
Micard V	199	Ruffo S	162
Iametti S	197	Degidio MG	161
Pasini G	192	Mariani BM	161

Sorumlu yazarların ülkeleri, makale sayıları, tüm makaleler arasındaki oranı ile tek veya çok ülke yazarlı makale sayısına ilişkin veriler Tablo 7 ve Şekil 4'te sunulmuştur. Elde edilen bulgular doğrultusunda, makarna konusundaki bilimsel üretimin %22,5'ini (637 makale) tek başına gerçekleştiren İtalya'nın alanda küresel bir lider konumunda olduğu görülmektedir. İtalya'yı sırasıyla ABD (298 makale, %10,5), Hindistan (193 makale, %6,8) ve Çin (110 makale, %3,9) izlemektedir.

Tablo 7. Sorumlu yazarların ülkeleri, makale sayıları, tüm makaleler arasındaki oranı ile tek veya çok ülke yazarlı makale sayısı

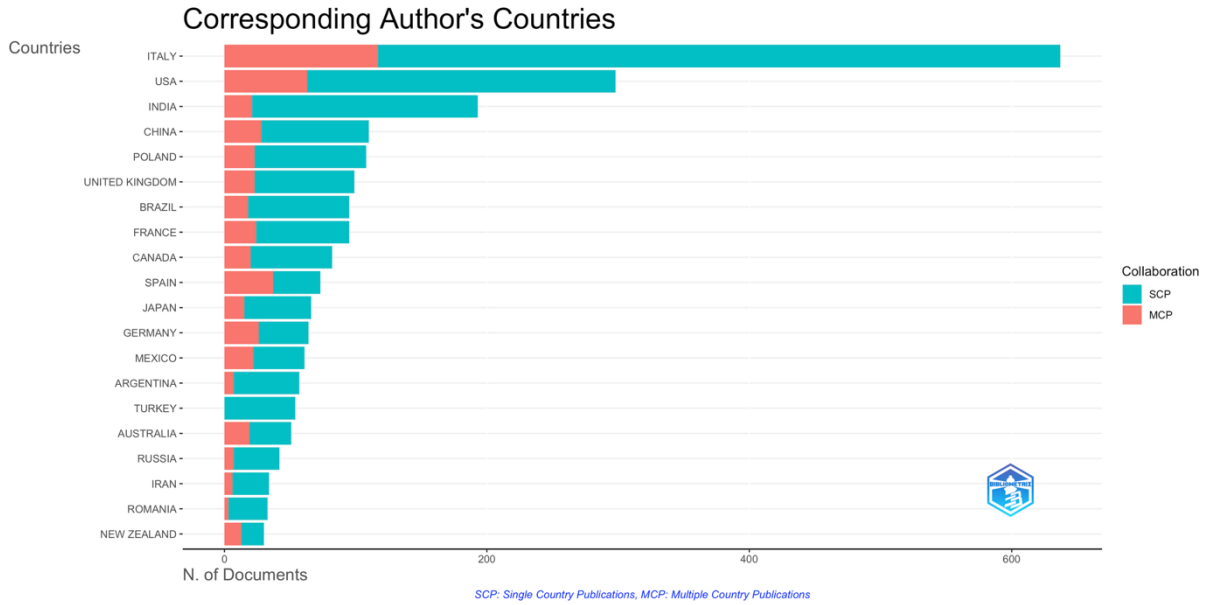
	Makale Sayısı	Toplam Makale Sayısına Oranı (%)	Tek Ülke Yazarlı Makale Sayısı	Çok Ülke Yazarlı Makale Sayısı
İtalya	637	22,5	520	117
ABD	298	10,5	235	63
Hindistan	193	6,8	172	21
Çin	110	3,9	82	28
Polanya	108	3,8	85	23
Birleşik Krallık	99	3,5	76	23
Brezilya	95	3,4	77	18
Fransa	95	3,4	71	24
Kanada	82	2,9	62	20
İspanya	73	2,6	36	37
Japonya	66	2,3	51	15
Almanya	64	2,3	38	26
Meksika	61	2,2	39	22
Arjantin	57	2,0	50	7
Türkiye	54	1,9	54	0
Avustralya	51	1,8	32	19
Rusya	42	1,5	35	7
İran	34	1,2	28	6
Romanya	33	1,2	30	3
Yeni Zelanda	30	1,1	17	13



Şekil 4. Ülkelerin makale sayılarına ait görsel (mavilik arttıkça makale sayısı artmaktadır)

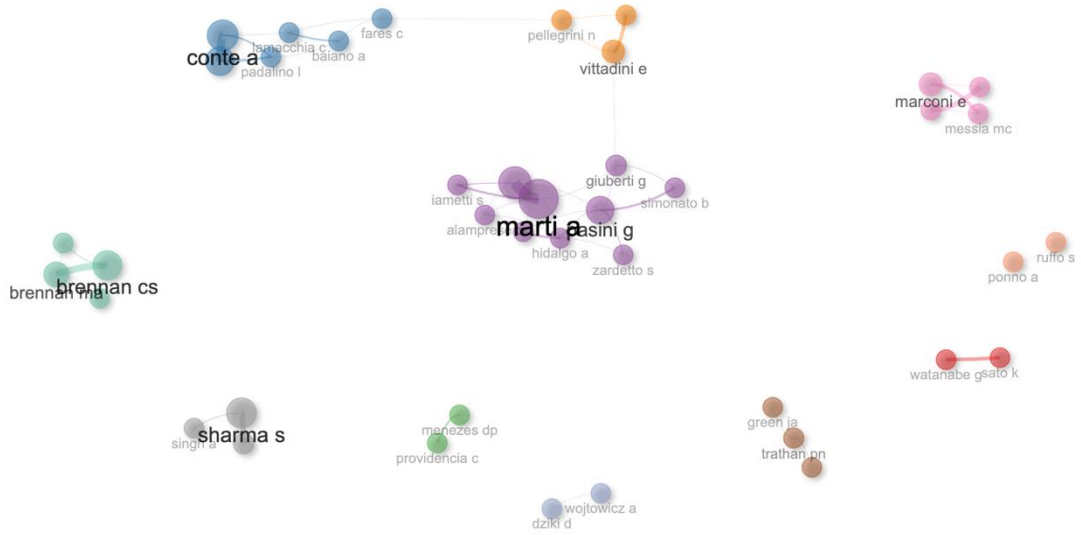
Ülkelerin uluslararası bilimsel iş birliği kapasiteleri değerlendirildiğinde, İtalya 117 çok ülke yazarlı makale ile ilk sırada yer alırken, İspanya toplam yayınlarının yaklaşık yarısını uluslararası ortaklıklarla yürüterek iş birliği oranı en yüksek ülkelerden biri olmuştur. Türkiye ise 54 makale (%1,9) ile 15. sırada

yer almakta olup, çalışmalarının tamamının tek ülke yazarlı olması ülkemizin bu alanda uluslararası araştırma ağlarına entegrasyonunu artırması gerektiğine işaret etmektedir (Tablo 7, Şekil 5).



Şekil 5. Sorumlu yazarların ülkeleri, makale sayıları, tek veya çok ülke yazarlı makale sayısı

Sorumlu yazarlar arasındaki iş birliği ağını gösteren harita Şekil 6'da sunulmuştur. Ağ haritasındaki renkli kümeler birlikte çalışan araştırma gruplarını, halka büyüklükleri yayın ağırlığını, bağlantı çizgileri ise yazarlar arasındaki ortak yayın ilişkilerini temsil etmektedir. Bulgular incelendiğinde, literatürdeki iş birliği ağının en güçlü ve merkezi kümesini Marti A ve Pasini G etrafında toplanan grubun (Iametti S, Giuberti G, Simonato B vb.) oluşturduğu görülmektedir. Bunun yanı sıra Conte A liderliğindeki küme ile Brennan CS merkezli araştırma grupları da alandaki diğer belirgin iş birliği odakları olarak öne çıkmaktadır. Genel olarak değerlendirildiğinde ise, makarna konusundaki yazarlık ağlarının tek bir küresel merkez yerine, belirli araştırmacıların liderliğinde şekillenen çok sayıda bağımsız ve kapalı araştırma grubu halinde yürütüldüğü görülmektedir.

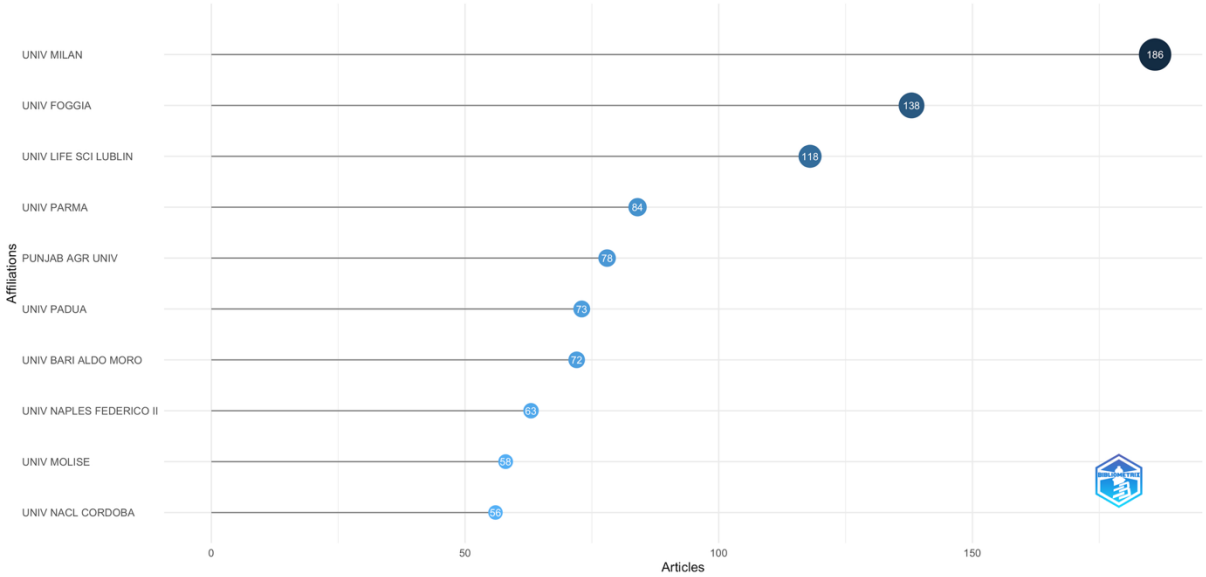


Şekil 6. Sorumlu yazarların iş birliği yaptığı yazar ağı

Makarna konusunda en fazla bilimsel yayın üreten ilk 20 kuruluşa ait veriler Tablo 8'de sunulmuştur. Tablodaki veriler incelendiğinde, literatüre en fazla katkı sağlayan kurumun 186 makale ile Milano Üniversitesi (Univ Milan) olduğu görülmektedir. Milano Üniversitesi'ni sırasıyla Foggia Üniversitesi (138 makale), Lublin Yaşam Bilimleri Üniversitesi (118 makale) ve Parma Üniversitesi (84 makale) izlemektedir. Elde edilen bulgular, makarna alanındaki akademik araştırmaların büyük oranda İtalyan üniversiteleri ve araştırma merkezleri bünyesinde yürütüldüğünü ortaya koymaktadır. İlk 20 sırada 13 İtalyan üniversitesinin yer alması, ülkenin alandaki güçlü kurumsal altyapısını ve nitelikli insan kaynağını yansıtmaktadır. Ayrıca Hindistan (Punjab Agr Univ, Cent Food Technol Res Inst), Arjantin (Univ Nacl Cordoba) ve ABD'deki (N Dakota State Univ) ziraat ve gıda odaklı kurumların listede üst sıralarda yer alması, hammadde üretimi ve gıda teknolojileri ekseninde kurumsal ilginin küresel ölçekte dağılım gösterdiğini doğrulamaktadır (Tablo 8, Şekil 7).

Tablo 8. Konu ile ilgili yayın yapan ilk 20 kuruluş ve makale sayıları

Kuruluş	Makale Sayısı	Kuruluş	Makale Sayısı
Univ Milan	186	Cent Food Technol Res Inst	55
Univ Foggia	138	Univ Bologna	52
Univ Life Sci Lublin	118	Univ Tuscia	51
Univ Parma	84	Univ Palermo	47
Punjab Agr Univ	78	Univ Cattolica Sacro Cuore	46
Univ Padua	73	Univ Florence	46
Univ Bari Aldo Moro	72	N Dakota State Univ	45
Univ Naples Federico Ii	63	Indiana Univ	43
Univ Molise	58	Univ Udine	42
Univ Nacl Cordoba	56	Lincoln Univ	39

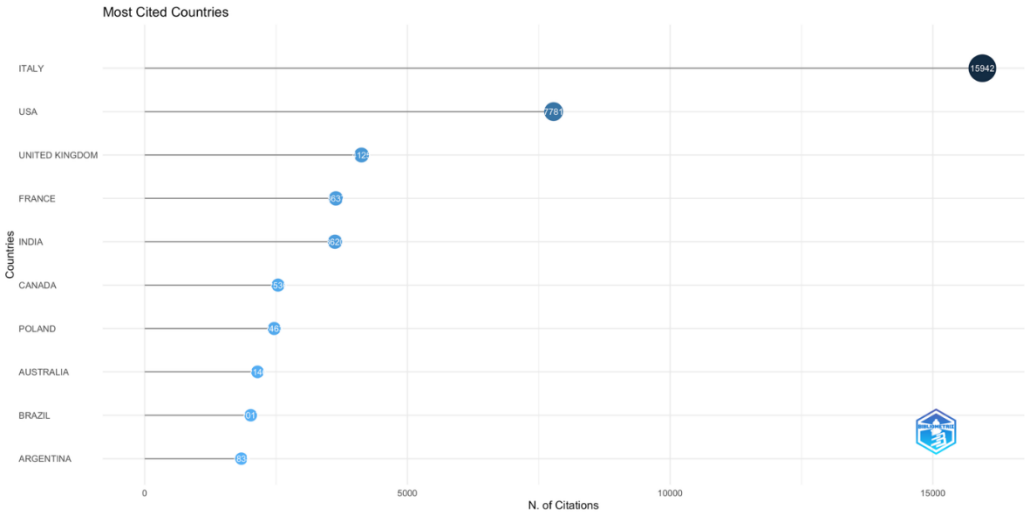


Şekil 7. Konu ile ilgili yayın yapan ilk 10 kuruluş ve makale sayıları

Makarna konusunda yayınlanan makalelerin aldıkları toplam atıf sayılarına göre ülkelerin sıralaması Şekil 8'de verilmiştir. Grafikten elde edilen bulgular doğrultusunda, İtalya'nın 15.942 atıf sayısı ile literatürdeki akademik etki liderliğini açık ara sürdürdüğü görülmektedir. İtalya'yı 7.781 atıf ile ABD, 4.125 atıf ile Birleşik Krallık ve 3.563 atıf ile Fransa izlemiştir.

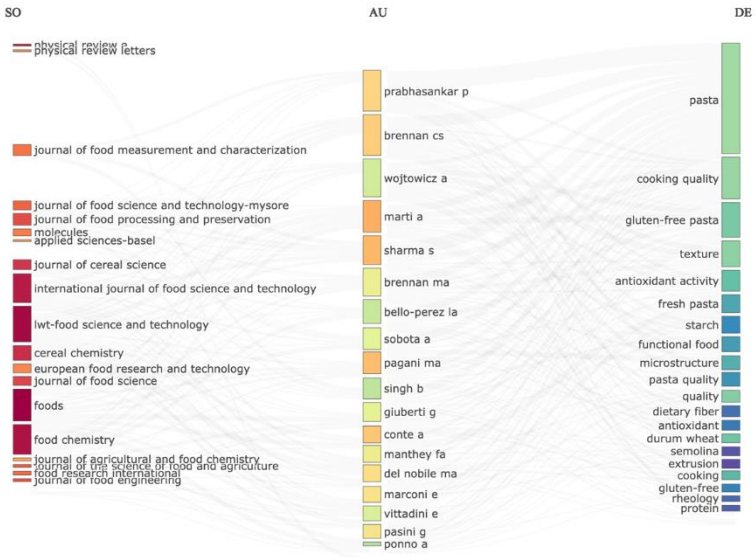
Ülkelerin toplam atıf sayıları değerlendirildiğinde, yayın hacminde olduğu gibi bilimsel etki (citation impact) boyutunda da İtalya ve ABD'nin domine edici bir role sahip olduğu anlaşılmaktadır. Bu iki ülkenin elde ettiği yüksek atıf oranları, bünyelerinde barındırdıkları araştırmacıların ve kurumların

makarna teknolojisi, gıda kimyası ile besinsel kalite üzerine yürüttükleri çalışmaların literatürde temel referans kaynakları olarak kabul gördüğünü göstermektedir.



Şekil 8. En çok atıf alan ülkeler sıralaması

Makalede dergiler (SO), yazarlar (AU) ve yazar anahtar kelimeleri (DE) arasındaki ilişkileri ve etkileşim akışını gösteren üç alanlı diyagram (Three-Fields Plot) verileri de incelenmiştir. Elde edilen bulgular doğrultusunda, makarna konusundaki çalışmaların temel olarak LWT-Food Science and Technology, International Journal of Food Science and Technology, Food Chemistry, Foods, Journal of Cereal Science ve Cereal Chemistry gibi gıda bilimi ve tahıl teknolojisi odaklı saygın dergilerde yoğunlaştığı görülmektedir. Prabhasankar P, Brennan CS, Wojtowicz A, Marti A ve Sharma S gibi alanda en üretken yazarların bu dergilerde sıklıkla yayın yaptığı ve çalışmalarını şekillendirdiği anlaşılmaktadır.
Yazarların çalıştıkları ana temalar (DE) ise ağırlıklı olarak pişme kalitesi (cooking quality), glutensiz makarna (gluten-free pasta), tekstürel özellikler (texture), antioksidan aktivite (antioxidant activity) ve fonksiyonel gıda (functional food) olarak tespit edilmiştir (Şekil 9).



Şekil 9. Dergi, yazar ve anahtar kelimeler seçilerek oluşturulan grafik

SONUÇ

Bu çalışmada, son elli yılda makarna alanında gerçekleştirilen bilimsel araştırmalar bibliyometrik bir yaklaşımla incelenmiştir. Elde edilen bulgular, akademik ilginin özellikle son yıllarda belirgin bir ivme kazandığını ve alanın istikrarlı biçimde büyüyen multidisipliner bir yapıya sahip olduğunu göstermektedir. Araştırma odağının geleneksel pişme kalitesi ve tekstürel parametrelerden; glutensiz formülasyonlar, fonksiyonel gıdalar, besinsel zenginleştirme ve yenilikçi proses teknolojilerine doğru evrildiği tespit edilmiştir. Küresel ölçekte İtalya ve ABD gibi ülkeler hem yayın hacmi hem de atıf etkisi açısından liderliği elinde tutarken, bilimsel üretimin ağırlıklı olarak gıda bilimi ve tahıl teknolojisi odaklı dergilerde yoğunlaştığı belirlenmiştir. Elde edilen sonuçlar doğrultusunda, Türkiye gibi üretimde dünyada söz sahibi olan ülkelerin uluslararası ortaklı projeler ve çok merkezli yayın ağlarına entegrasyonu güçlendirilmelidir. Ayrıca tarladan sofraya uzanan değer zincirinde agronomik, biyoteknolojik ve tüketici odaklı araştırmalar bir bütün olarak ele alınmalı; sağlıklı beslenmeye uygun olarak glisemik indeksi düşük, yüksek lifli ve sürdürülebilir hammadde kaynaklarıyla zenginleştirilmiş ürün geliştirme çalışmalarına öncelik verilmelidir.

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PRUSYA MİRASI VE NASYONAL SOSYALİZM KISKACINDA POLONYA: VERSAY'IN RÖVANŞINDAN DANZİG KRİZİNE GİDEN SÜREÇ

POLAND UNDER THE SHADOW OF PRUSSIAN HERITAGE AND NATIONAL SOCIALISM: FROM THE REVANCHISM OF VERSAILLES TO THE DANZIG CRISIS

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Öz
1919 Versay Antlaşması ile Polonya devletinin yeniden kurulması ve Doğu Prusya'yı Weimar Almanyası'ndan ayıran Danzig Koridoru'nun yaratılması, Alman devlet aklında telafisi imkânsız bir travma doğurmuştur. Bu travma, geleneksel Prusya askeri ekolü ile Adolf Hitler'in nasyonal sosyalist ideolojisi arasında Polonya karşıtı tarihsel bir mutabakat inşa etmiştir. Alman askeri ve bürokratik elitleri Batı'daki ezeli rakiplerine karşı klasik bir askeri saygı ve profesyonel rekabet beslerken Polonya'yı toprak gasp eden yapay bir devlet olarak görmüş ve ona karşı ırksal-mekânsal bir hınç biriktirmiştir. Hitler açısından ise Polonya, Kavgam kitabında formüle edilen Lebensraum (Hayat Sahası) doktrininin ilk ve kaçınılmaz tasfiye hedefidir. 1933-1939 yılları arasında Hitler ve Alman askeri karar alıcılarının Polonya'ya bakışındaki ideolojik süreklilik ve askeri elitin rövanşizmi kronolojik bir düzlemde üç ana aşamada somutlaşmıştır. İlk olarak Hitler'in iktidara geldikten sonra Polonya ile imzaladığı 1934 Saldırmazlık Paktı, yayılmacı hedeflerden vazgeçiş değil; Batı cephesinde elini güçlendirene ve yeniden silahlanma programını tamamlayana kadar Doğu'da zaman kazanma stratejisidir. İkinci aşamada, Münih Konferansı sonrasında Çekoslovakya'nın parçalanmasıyla birlikte baskı artmış; Danzig'in iadesi ve eksterritoryal bir ulaşım koridoru talebi masaya konmuştur. Üçüncü ve nihai aşamada ise, Polonya'nın İngiltere ve Fransa'dan güvenlik garantisi alarak bu talepleri reddetmesiyle kâğıt üzerindeki manevralar bitmiş ve Kavgam'daki asıl imha konsepti devreye sokulmuştur. Danzig Krizi, sadece konjonktürel bir sınır anlaşmazlığı değil, Versay düzenini yıkarak Doğu Avrupa'yı Almanlaştırmak isteyen Prusya intikamcılığı ile Nazi yayılmacılığının ortak patlama noktası olmuştur. Sonuç olarak bu çalışma, İkinci Dünya Savaşı'nın çıkış nedenlerini sadece taktiksel krizler üzerinden değil, Alman devlet aklındaki tarihsel ve ideolojik Polonya karşıtlığı üzerinden yeniden okumayı amaçlamaktadır.
Anahtar Kelimeler: Almanya, Danzig, Lebensraum, Prusya, Polonya

Abstract
The reconstitution of the Polish state by the 1919 Treaty of Versailles and the creation of the Danzig Corridor, which severed East Prussia from Weimar Germany, inflicted an irreparable trauma on the German state mind. This trauma forged an anti-Polish historical consensus between the traditional Prussian military school and Adolf Hitler's National Socialist ideology. While the German military and bureaucratic elites harbored a classic military respect and professional rivalry toward their arch-rivals in the West, they viewed Poland as an artificial state usurping their territory and accumulated a racial-spatial resentment against it. For Hitler, Poland was the first and inevitable target of liquidation under the doctrine of *Lebensraum* (Living Space) formulated in his book *Mein Kampf*. Between 1933 and 1939, the ideological continuity in the perspective of Hitler and German military decision-makers toward Poland, combined with the revanchism of the military elite, materialized chronologically in three main phases. First, the 1934 Non-Aggression Pact signed with Poland after Hitler came to power was not a renunciation of expansionist goals, but a strategy to buy time in the East until Germany could strengthen its hand on the Western front and complete its rearmament program. In the second phase, following the Munich Conference and the partition of Czechoslovakia, pressure mounted; the return of Danzig and the demand for an extraterritorial transport corridor were put on the table. In the third and final phase, as Poland rejected these demands by securing security guarantees from Britain and France, the maneuvers on paper came to an end and the actual concept of annihilation in *Mein Kampf* was set in motion. The Danzig Crisis was not merely a conjectural border dispute, but the joint eruption point of Prussian revanchism and Nazi expansionism, both seeking to overthrow the Versailles order and Germanize Eastern Europe. Consequently, this study aims to re-read the causes of the outbreak of the

Second World War not merely through tactical crises, but through the historical and ideological anti-Polish sentiment within the German state mind.

Keywords: Germany, Danzig, Lebensraum, Prussia, Poland

THE EPISTEMIC NEAR-MISS AND GOTHIC INTUITION IN FEMALE KNOWLEDGE IN "CHRISTABEL" AND NORTHANGER ABBEY

"CHRISTABEL" VE NORTHANGER ABBEY ESERLERİNDE KADIN BİLGİSİNDE GOTİK SEZGİ VE EPİSTEMİK KIL PAYI YANILGI

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Abstract
This study examines the relationship between Samuel Taylor Coleridge's poem "Christabel" (1816) and Jane Austen's novel *Northanger Abbey* (1817) through their contemporaneous investigations of the epistemic vulnerabilities of women and the conditions under which women's perceptions of danger are made valid or made invalid. Both "Christabel" and *Northanger Abbey* are studied together because both rely on Gothic elements of secrecy, ambiguity, threat, uncertain evidence, and interpretation to create a crisis of knowledge. In each text, the Gothic becomes a space wherein the woman's intuition is tested against the patriarchal voice and modes of rational thinking. In light of Miranda Fricker's concepts of testimonial and hermeneutical injustice, as well as Kristie Dotson's theory of epistemic silencing, the study argues that Coleridge and Austen use Gothic intuition to show two different forms in which women have been marginalized in their epistemology: Christabel's knowledge is silenced, while Catherine Morland's knowledge is corrected because its interpretation is factually incorrect but perceptive. Christabel possesses both experiential and bodily knowledge of the threat posed by Geraldine, but gradually finds herself unable to transform such knowledge into credible evidence. Hence, her story demonstrates epistemic silencing because she possesses knowledge that is never made part of the credibility economy. On the other hand, while Catherine is aware that General Tilney represents an embodiment of patriarchy's menace, her identification of him as such occurs through the conventions of the Gothic, turning her valid perception into a false story about criminality. This study describes Catherine's condition as an example of "epistemic near-miss," which involves a kind of knowledge where the literal interpretation is mistaken, but the actual perception of danger is accurate. Reading both texts together reveals that Gothic intuition is neither irrational nor exaggerated, but may serve as another mode of understanding patriarchal power. Therefore, female epistemic vulnerability results not only from the limitations in knowledge but from structural arrangements that govern whose perceptions are speakable, believable, and socially meaningful.
Keywords: Epistemic silencing, testimonial and hermeneutical injustice, Gothic intuition, *Christabel*, *Northanger Abbey*

Özet
Bu çalışma, Samuel Taylor Coleridge'in "Christabel" (1816) adlı şiiri ile Jane Austen'ın *Northanger Abbey* (1817) adlı romanı arasındaki ilişkiyi, kadınların epistemik kırılganlıklarına ve kadınların tehlikeye ilişkin algılarının hangi koşullar altında geçerli sayıldığı ya da geçersiz kılındığına yönelik dönemdaş incelemeleri üzerinden ele almaktadır. "Christabel" ve *Northanger Abbey*, gizlilik, belirsizlik, tehdit, kesinlikten yoksun kanıt ve yorumlama gibi Gotik unsurlardan yararlanarak bir bilgi krizini sahnelemeleri nedeniyle birlikte ele alınmaktadır. Her iki eserde de Gotik, kadın sezgisinin ataerkil otorite ve toplumsal olarak kabul gören akılcı düşünme biçimleri karşısında sınandığı bir alan işlevi görür. Miranda Fricker'ın "tanıklık adaletsizliği ve yorumsal adaletsizlik" kavramları ile Kristie Dotson'ın "epistemik susturma" kuramından hareket eden bu çalışma, Coleridge ve Austen'ın Gotik sezgiyi kadınların epistemik açıdan ötekileştirilmesinin iki farklı biçimini ortaya koymak için kullandıklarını ileri sürmektedir: Christabel'in bilgisi susturulurken, Catherine Morland'ın bilgisi, yorumu olgusal açıdan yanlış fakat algısal açıdan isabetli olduğu için disipline edilip düzeltilmektedir. Christabel, Geraldine'in oluşturduğu tehdide ilişkin hem deneyimsel hem de bedensel bilgiye sahiptir; ancak bu bilgiyi giderek güvenilir bir tanıklığa dönüştüremez hâle gelir. Dolayısıyla onun deneyimi, bilginin mevcut olmasına rağmen güvenilirlik ekonomisine dâhil edilemediği epistemik susturma olgusunun bir örneğini oluşturur. Catherine ise General Tilney'nin ataerkil bir tehdit oluşturduğunu doğru biçimde sezer; ancak bu sezgiyi Gotik anlatının kalıpları aracılığıyla yorumlayarak geçerli bir güç algısını olgusal açıdan yanlış bir suç anlatısına dönüştürür. Bu çalışma Catherine'in durumunu "epistemik kıl payı yanılgı" olarak tanımlamaktadır: olgusal yorumun yanlış olduğu, ancak altta yatan

tehlike algısının isabetli kaldığı bir bilme biçimi. İki metnin birlikte okunması, Gotik sezginin yalnızca irrasyonel ya da abartılı olmadığını, aksine ataerkil iktidarı kavramanın alternatif bir yolu olarak işlev görebileceğini göstermektedir. Dolayısıyla kadınların epistemik kırılganlığı yalnızca bilgisizlikten kaynaklanmaz; aynı zamanda kimin algısının dile getirilebilir, inanılır ve toplumsal açıdan anlamlı kabul edileceğini belirleyen yapısal düzenlemeler tarafından da üretilir.

Anahtar Kelimeler: Epistemik susturma, tanıklık ve yorumsal adaletsizlik, Gotik sezgi, "Christabel," *Northanger Abbey*

HIGH-HEELED OR FLAT? EXAMINING WOMEN MANAGERS' FOOTWEAR CHOICES IN THE CONTEXT OF AUTHORITY, POWER, AND PROFESSIONAL IDENTITY

TOPUKLU MU, TOPUKSUZ MU? KADIN YÖNETİCİLERİN AYAKKABI TERCİHLERİNİN OTORİTE, GÜÇ VE PROFESYONEL KİMLİK BAĞLAMINDA İNCELENMESİ

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Abstract
This study aims to examine women managers' perceptions of the high-heeled or flat footwear they prefer in the workplace and the meanings they attribute to these choices within the dimensions of authority, power, and professional identity. A qualitative research approach was adopted, and semi-structured interviews were used as the data collection method. The study group consisted of nine middle- and senior-level women managers working in different sectors in Karaman, Türkiye. Participants were selected based on the criterion of having managerial experience in line with the purpose of the study, using purposive sampling. The interviews addressed participants' footwear preferences in the workplace, the factors influencing these preferences, and changes in their footwear choices under different working conditions; the meanings attributed to these choices were evaluated in the context of authority, power, and professional identity. The data were analyzed using descriptive and content analysis methods. The findings indicate that women managers' footwear preferences are not limited to aesthetic considerations and physical comfort. While participants who preferred high-heeled footwear associated this choice with authority, power, self-confidence, professionalism, and a managerial appearance, those who preferred flat footwear defined managerial authority independently of footwear, in terms of knowledge, experience, character, and behavior. The findings also indicate that working conditions, physical comfort, freedom of movement, and the level of formality of the setting are important determinants of footwear preferences. In this respect, the study demonstrates that women managers' footwear choices carry multidimensional meanings related to appearance and self-perception, shaped by managerial experience and working conditions, and contributes to understanding footwear choice as an element that acquires meaning within these contexts.

Keywords: Women Managers, High-heeled Footwear, Footwear Choice, Authority, Power, Professional Identity

Öz
Bu araştırmanın amacı, kadın yöneticilerin iş yaşamında tercih ettikleri yüksek topuklu veya topuksuz ayakkabılara ilişkin algılarını ve bu tercihlere yükledikleri anlamları otorite, güç ve profesyonel kimlik boyutları çerçevesinde incelemektir. Araştırmada nitel araştırma yaklaşımı benimsenmiş ve veri toplama yöntemi olarak yarı yapılandırılmış görüşme tercih edilmiştir. Araştırmanın çalışma grubunu, Karaman ilinde farklı sektörlerde görev yapan 9 orta ve üst düzey kadın yönetici oluşturmaktadır. Katılımcıların belirlenmesinde, araştırmanın amacı doğrultusunda yöneticilik deneyimine sahip olma ölçütü esas alınmış olup amaçlı örnekleme yöntemi kullanılmıştır. Görüşmelerde katılımcıların iş yaşamındaki ayakkabı tercihleri, tercihlerini etkileyen unsurlar ve farklı çalışma koşullarında ayakkabı tercihlerindeki değişimler ele alınmış; bu tercihlere yükledikleri anlamlar otorite, güç ve profesyonel kimlik bağlamında değerlendirilmiştir. Elde edilen veriler, betimsel analiz ve içerik analizi yöntemleriyle çözümlenmiştir. Bulgular, kadın yöneticilerin ayakkabı tercihlerinin yalnızca estetik ve fiziksel rahatlıkla sınırlı olmadığını; yüksek topuklu ayakkabı tercih eden katılımcıların bu tercihi otorite, güç, özgüven, profesyonellik ve yönetici görünümüyle ilişkilendirirken, topuksuz ayakkabı tercih edenlerin yöneticilik otoritesini ayakkabıdan bağımsız olarak bilgi, deneyim, karakter ve davranış üzerinden tanımladığını göstermektedir. Ayrıca çalışma koşulları, fiziksel rahatlık, hareket özgürlüğü ve bulunulan ortamın resmiyet düzeyinin ayakkabı tercihlerinde belirleyici olduğu görülmektedir. Bu yönüyle araştırma, kadın yöneticilerin ayakkabı tercihlerinin yöneticilik deneyimi ve çalışma koşullarıyla şekillenen,

görünüm ve benlik algısına ilişkin çok boyutlu anlamlar taşıdığını ortaya koymakta ve ayakkabı tercihinin bu bağlamlarda anlam kazanan bir unsur olarak değerlendirilmesine katkı sağlamaktadır.
Anahtar Kelimeler: Kadın Yöneticiler, Yüksek Topuklu Ayakkabılar, Ayakkabı Tercihi, Otorite, Güç, Profesyonel Kimlik

ARTIFICIAL INTELLIGENCE TRANSFORMATION IN ACCOUNTING RECORDS: DETECTION OF SEMANTIC–ACCOUNTING INCONSISTENCIES IN TURKISH E-DOCUMENTS USING EXPLAINABLE ARTIFICIAL INTELLIGENCE

MUHASEBE KAYITLARINDA YAPAY ZEKA DÖNÜŞÜMÜ: AÇIKLANABİLİR YAPAY ZEKA KULLANILARAK TÜRK E-BELGELERİNDEKİ ANLAMSAL-MUHASEBESEL TUTARSIZLIKLARIN TESPİTİ

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ABSTRACT
With the increasing adoption of electronic documents, the volume of data generated in accounting processes has expanded substantially. Consequently, the reliability of accounting records depends not only on technical data entry but also on whether the content of an electronic document is semantically and accounting-wise consistent with the transaction recorded. This study proposes an explainable artificial intelligence architecture for detecting semantic and accounting inconsistencies in Turkish electronic documents, particularly e-Invoices and similar e-documents. The proposed system combines natural language processing of document descriptions with structured accounting variables, including transaction amounts, VAT rates, document dates, account codes, debit-credit relationships, document types, and accounting periods. Turkish document text will first be transformed into contextual semantic representations through an NLP-based approach. These representations will then be integrated with rule-based accounting controls and a machine learning-based risk model to generate a risk score for each prospective accounting record. Rather than producing only a binary decision such as “appropriate” or “suspicious,” the system is designed to provide an evidence-based explanation indicating which textual and accounting characteristics contributed to the detected risk. The research will adopt a design science methodology and evaluate the prototype using synthetic and anonymized accounting records. Model performance will be assessed through precision, recall, F1-score, ROC-AUC/PR-AUC, explanation accuracy, and expert evaluation time. Comparative experiments will examine rule-based, structural-feature-only, NLP-only, and hybrid approaches. The expected contribution is a Turkish accounting-domain-oriented, explainable, human-in-the-loop quality-control architecture that can identify potential inconsistencies before records are finalized. The study aims to extend accounting automation beyond account-code recommendation toward proactive error prevention, risk prioritization, and accountable human–AI collaboration.
KEYWORDS: Artificial intelligence; natural language processing; accounting information systems; e-documents; explainable artificial intelligence; anomaly detection; semantic consistency; accounting automation

ÖZET
Elektronik belge kullanımının giderek yaygınlaşmasıyla birlikte muhasebe süreçlerinde üretilen veri hacmi önemli ölçüde artmıştır. Buna bağlı olarak muhasebe kayıtlarının güvenilirliği yalnızca teknik veri girişine değil, elektronik belge içeriğinin oluşturulan işlemle anlamsal ve muhasebesel açıdan tutarlı olmasına da bağlı hâle gelmiştir. Bu çalışmada, özellikle e-Fatura ve benzeri elektronik belgelerdeki semantik ve muhasebesel tutarsızlıkların tespit edilmesine yönelik açıklanabilir yapay zekâ tabanlı bir mimari önerilmektedir. Önerilen sistem; belge açıklamalarının doğal dil işleme yöntemleriyle analiz edilmesini, işlem tutarları, KDV oranları, belge tarihleri, hesap kodları, borç-alacak ilişkileri, belge türleri ve muhasebe dönemleri gibi yapısal muhasebe değişkenleriyle birlikte değerlendirilmesini kapsamaktadır. Türkçe belge metinleri ilk olarak NLP tabanlı bir yaklaşımla bağlamsal anlamsal temsillere dönüştürülecektir. Daha sonra bu temsiller, kural tabanlı muhasebe kontrolleri ve makine öğrenmesi tabanlı bir risk modeli ile bütünleştirilerek her bir muhasebe kaydı için risk skoru

üretilecektir. Sistem, yalnızca "uygun" veya "şüpheli" şeklinde ikili bir karar vermek yerine, tespit edilen riskin hangi metinsel ve muhasebesel özelliklerden kaynaklandığını kanıta dayalı olarak açıklayacak şekilde tasarlanmıştır. Araştırmada tasarım bilimi metodolojisi benimsenerek prototip sistem sentetik ve anonimleştirilmiş muhasebe kayıtları kullanılarak değerlendirilecektir. Model performansı precision, recall, F1-score, ROC-AUC/PR-AUC, açıklama doğruluğu ve uzman değerlendirme süresi ölçütleri üzerinden incelenecektir. Karşılaştırmalı deneylerde kural tabanlı, yalnızca yapısal özelliklere dayalı, yalnızca NLP tabanlı ve hibrit yaklaşımlar değerlendirilecektir. Çalışmanın beklenen katkısı, Türkçe muhasebe alanına özgü, açıklanabilir ve insan-döngüde (human-in-the-loop) çalışan bir kalite kontrol mimarisinin geliştirilmesidir. Bu mimarinin, muhasebe kayıtları kesinleştirilmeden önce olası tutarsızlıkları belirlemesi ve muhasebe otomasyonunu hesap kodu önerisinin ötesine taşıyarak proaktif hata önleme, risk önceliklendirme ve hesap verebilir insan–yapay zekâ iş birliğine katkı sağlaması amaçlanmaktadır.

ANAHTAR KELİMELER: Yapay zekâ; doğal dil işleme; muhasebe bilgi sistemleri; e-belge; açıklanabilir yapay zekâ; anomali tespiti; semantik tutarlılık; muhasebe otomasyonu.

MULTILINGUAL SPEECH EMOTION RECOGNITION: AN XLS-R-BASED APPROACH COMBINING TURKISH, POLISH, AND URDU CORPORA

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Abstract
This study addresses speech emotion recognition (SER) in a multilingual setting by combining three emotional speech corpora from three different languages Turkish (TurEV-DB), Polish (nEMO), and Urdu (URDU-Dataset) within a common emotion label space. Because the corpora label emotions with different strings and differ substantially in utterance duration and recording conditions, a careful harmonization and preprocessing pipeline is applied. Emotion labels are mapped to a common canonical space, and only the three classes consistently represented across all three corpora (angry, happy, sad) are retained. All recordings are resampled to 16 kHz, converted to mono, and segmented into fixed one-second windows, and low-energy segments are discarded. Each corpus–emotion cell is then downsampled to an equal number of examples, producing a set balanced with respect to both class and language (2,115 segments). To obtain realistic performance estimates, a stratified, group-based split (StratifiedGroupKFold) keeps all segments derived from the same original recording on the same side of the split, thereby preventing data leakage. The multilingually pretrained wav2vec2-XLS-R-300M model is fine-tuned with its convolutional feature encoder frozen. On the balanced test set, the model attains an overall accuracy of 90.9% and a macro-F1 score of 0.909. The results indicate that multilingually pretrained speech representations can be fine-tuned into high-performing emotion classifiers even with limited and heterogeneous multilingual data, provided that label harmonization, corpus and class balancing, and leakage-safe splitting are handled explicitly.
Keywords: Speech emotion recognition, multilingual learning, transfer learning, wav2vec2, XLS-R.

1. Introduction

Speech emotion recognition (SER) aims to automatically infer a speaker's affective state from acoustic signals, and it has become increasingly relevant for applications such as human–computer interaction, call-center analytics, healthcare, and dialogue personalization (El Ayadi et al., 2011; Akçay & Oğuz, 2020). Much of the emotional information in speech is carried by prosodic and spectral characteristics pitch, energy, rhythm, and voice quality which can, in principle, transcend the lexical content and even the language being spoken. This language-independent dimension of vocal emotion is precisely what makes multilingual and cross-lingual SER a plausible undertaking, yet it also exposes systems to confounds that arise when data are aggregated across languages and recording conditions.

In recent years, self-supervised speech representation models have substantially advanced the field. Models such as wav2vec 2.0 learn general-purpose speech representations from large amounts of unlabeled audio and can subsequently be fine-tuned for downstream tasks with comparatively little labeled data (Baevski et al., 2020). This paradigm is particularly attractive for SER, where labeled emotional corpora are typically small: features extracted from pretrained wav2vec 2.0 models have been shown to outperform traditional hand-crafted descriptors even with shallow downstream classifiers (Pepino et al., 2021), and transfer learning from self-supervised backbones has repeatedly proven effective under low-resource conditions (Nasersharif & Azad, 2023; Jafarzadeh et al., 2024). The multilingual successor of wav2vec 2.0, XLS-R, is pretrained on data spanning 128 languages and yields

representations that transfer well across languages (Babu et al., 2022), making it a natural backbone for multilingual speech tasks.

Despite this progress, most SER research remains concentrated on a small number of high-resource languages, and datasets for many languages are scarce (Akçay & Oğuz, 2020). Recent efforts have begun to close this gap by releasing emotional speech corpora for under-resourced languages, including Turkish (Canpolat et al., 2020), Polish (Christop, 2024), and Urdu (Latif et al., 2018; Zaheer et al., 2023). However, these corpora were created independently: they adopt different emotion label sets and naming conventions, vary in utterance structure (isolated words, full sentences, or spontaneous excerpts), and were recorded under different conditions (acted vs. spontaneous). A well-documented consequence is that SER systems trained and evaluated within a single corpus degrade sharply when transferred to unseen corpora or languages (Latif et al., 2023), and that models readily overfit to corpus-specific artifacts rather than learning genuinely emotion-bearing cues (Parry et al., 2019; Zhang et al., 2019). Naively pooling heterogeneous corpora can therefore allow a model to exploit corpus- or language-specific shortcuts, and can inflate reported performance when evaluation is not designed to prevent it cross-corpus validation typically yields substantially lower, and more realistic, estimates than same-corpus validation (Talpur et al., 2025).

The work most closely related to the present study applies multilingual self-supervised backbones to emotion recognition across languages. XLS-R has been used directly as an end-to-end multilingual SER model (Das & Haque, 2025), and large speech models from the wav2vec 2.0 and Whisper families have been systematically compared as cross-lingual feature extractors across many languages (D'Asaro et al., 2024). What remains comparatively underexplored is the joint combination of three typologically and acoustically dissimilar under-resourced languages Turkish, Polish, and Urdu within a single, explicitly harmonized label space, together with an evaluation protocol that guards against the specific confounds introduced by such heterogeneity.

This study investigates whether a multilingually pretrained model can be fine-tuned into a robust emotion classifier when three such heterogeneous corpora are combined. The main contributions are as follows: (i) a harmonization and preprocessing pipeline that unifies emotion labels, standardizes sampling rate and duration through fixed one-second windowing, and balances the data with respect to both class and language; (ii) a leakage-safe, group-based evaluation protocol that prevents segments originating from the same recording from appearing in both the training and test sets; and (iii) an empirical evaluation of a fine-tuned XLS-R model, reported both overall and per corpus, together with an explicit discussion of the distinction between in-domain and genuine cross-lingual performance.

2. Literature Review

Self-supervised representations and transfer learning for SER

The dominant trend in contemporary SER is the reuse of self-supervised speech representation learning (S3RL) models wav2vec 2.0, HuBERT, and WavLM as feature extractors or fine-tuning backbones (Baevski et al., 2020; Babu et al., 2022). Because emotional corpora are small, transferring knowledge from models pretrained on large unlabeled speech collections mitigates data scarcity. Pepino et al. (2021) showed that combining representations from multiple internal layers of a pretrained wav2vec 2.0 model, fed to shallow classifiers, surpasses systems based on spectrograms or earlier wav2vec features. Jafarzadeh et al. (2024) compared Wav2Vec2 and HuBERT as automatic feature extractors across several benchmark corpora, confirming the robustness of S3RL features relative to hand-crafted descriptors. Because the massive parameter counts of these backbones complicate fine-tuning for low-resource SER, Nasersharif and Azad (2023) proposed a compact model that transfers the HuBERT convolutional encoder and replaces its transformer stack with a lightweight conformer block, attaining performance comparable to full S3RL models. Fine-tuning strategy has itself been a subject of study: Gao et al. (2023) introduced a two-stage fine-tuning scheme that first adapts wav2vec 2.0 with automatic speech recognition and gender pretraining before emotion fine-tuning, alleviating gradient conflicts and improving downstream accuracy. Beyond the wav2vec family, WavLM-derived domain emotion embeddings have been applied to both single- and cross-lingual SER (Yang et al., 2024), and D'Asaro et al. (2024) benchmarked English-only and multilingual large speech models including XLS-R and Whisper as cross-lingual feature extractors, reporting that the optimal representation layer and the benefit of multilingual pretraining depend on both the backbone family and the target language. These

findings collectively motivate the use of a multilingually pretrained backbone, with a frozen convolutional encoder, as adopted in the present study.

Cross-corpus and cross-lingual generalization

A recurring finding across the literature is that SER systems generalize poorly beyond the corpus on which they were trained. Parry et al. (2019) analyzed several deep architectures under cross-corpus training with six corpora and observed that recurrent models tend to overfit the specific corpora present in training, whereas convolutional models generalize better to an unseen corpus evidence that aggregated training data can encourage the learning of corpus identity rather than emotion. Zhang et al. (2019) framed corpus, domain (spoken vs. sung), and speaker gender as explicit sources of variability and used multi-task learning to model them jointly, finding that cross-corpus performance generally improves as more training corpora are added. In genuinely cross-lingual settings, Latif et al. (2023) demonstrated that both cross-corpus and cross-language transfer suffer from large domain gaps and proposed a self-supervised adversarial dual-discriminator network to learn domain-invariant, emotionally discriminative representations without target labels.

Multilingual and cross-lingual evaluations have since expanded to more diverse language sets, including Amharic against several other languages (Retta et al., 2023) and combinations of Urdu, English, German, and Italian using hybrid deep and transformer-based models (Almadhor et al., 2026). To address the twin obstacles of distribution shift and scarce target-language labels, Agarla et al. (2024) proposed a semi-supervised transformer-based method that leverages a small number of labeled target-language examples, while Lu et al. (2026a) combined multi-wavelet data augmentation with contrastive feature decoupling to isolate language-invariant emotion representations. These studies establish cross-lingual generalization as the central open problem that motivates careful, leakage-aware experimental design.

Domain adaptation and domain generalization

A substantial body of work reduces the source–target discrepancy through explicit domain adaptation or domain generalization. Gao et al. (2022) applied domain-adversarial training together with center loss to suppress non-affective information and tighten intra-class feature distributions, improving both cross-corpus and multi-corpus evaluation. This line was extended by an adversarial domain-generalized transformer that fuses supervised and pretrained features via a gated mechanism to learn a shared source–target distribution (Gao et al., 2024). Feature-transformation approaches include the triplet-network preprocessing of Lee (2021), which learns corpus-invariant emotional features and reports large cross-corpus gains across English and Japanese corpora, and the generalized subspace distribution adaptation framework of Li et al. (2023), which learns a shared low-dimensional subspace and a divergence-reducing distance metric between corpora. Domain adaptation has also been directed at the speaker as a nuisance factor: Lu et al. (2026b) recast speaker-independent SER as multi-source domain adaptation, using joint distribution adaptation and a dynamic balance factor to handle unseen-speaker distributions. Although the present study does not employ adversarial adaptation, this literature underscores why speaker- and corpus-level variability must be controlled, and it frames the leave-one-language-out protocol proposed here as future work as the natural test of genuine domain generalization.

Under-resourced languages and emotional speech corpora

Progress in multilingual SER depends on the availability of emotional corpora for languages beyond English, German, and Italian. For Turkish, TurEV-DB provides word-level utterances in four emotional categories, produced by amateur actors and denoised after recording (Canpolat et al., 2020). For Polish, the nEMO corpus offers sentence-level simulated emotional speech recorded by professional actors (Christop, 2024). For Urdu, two complementary resources exist: the URDU dataset of spontaneous emotional excerpts drawn from television talk shows (Latif et al., 2018), and the larger scripted SEMOUR+ repository of emotion-tagged speech from native speakers (Zaheer et al., 2023). The heterogeneity across these corpora word- versus sentence- versus discourse-level units, and acted versus spontaneous elicitation is precisely the source of variability that complicates their combination. Talpur et al. (2025) made this concrete for Urdu by validating SER models across three Urdu corpora and showing that same-corpus evaluation can overestimate unweighted average recall by up to roughly thirteen percentage points relative to cross-corpus evaluation, reinforcing the need for realistic, cross-corpus-aware protocols.

Data balancing, evaluation, and leakage

Finally, a smaller but important strand of work emphasizes that dataset construction and evaluation design materially affect reported results. Corpus and class imbalance can bias models toward majority sources, and unprincipled data partitioning can allow near-duplicate material to appear on both sides of a split. Bano et al. (2026) addressed this directly when constructing a balanced multimodal emotion benchmark, curating a class-balanced subset and enforcing strict movie- and series-level splits to prevent content overlap between partitions and thereby enable more reliable generalization estimates. Together with the cross-corpus overestimation reported by Talpur et al. (2025) and the corpus-overfitting behavior documented by Parry et al. (2019), these observations motivate the methodological emphasis of the present study: simultaneous balancing of language and class, uniform windowing to neutralize utterance-duration cues, and group-based, leakage-safe splitting that keeps all segments of a given recording on a single side of the partition.

Positioned against this literature, the present study combines three under-resourced languages that have not, to our knowledge, been jointly modeled within a unified label space, and it foregrounds the harmonization, balancing, and leakage-prevention steps that much prior work treats only implicitly.

3. Methodology

The overall experimental pipeline, spanning source corpora, data preparation, and evaluation, is summarized in Figure 1. It is organized into three stages: preprocessing, in which emotion labels are harmonized and the audio is standardized and segmented; dataset preparation, in which the segmented data are balanced across classes and languages and then partitioned in a leakage-safe manner; and modeling and evaluation, in which a multilingually pretrained backbone is fine-tuned and assessed. Each stage is described in the following subsections.

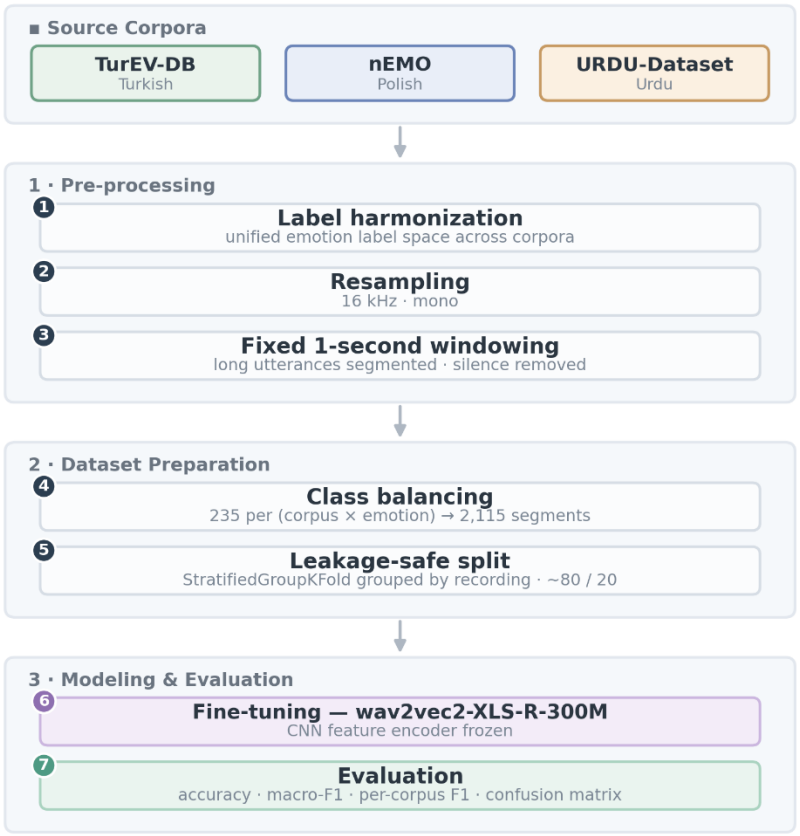


Figure 1. Overview of the proposed multilingual SER pipeline.

Datasets

Three publicly available emotional speech corpora, each representing a different language and recording condition, were combined for this study. TurEV-DB (Canpolat et al., 2020) is a Turkish corpus of short, word-level utterances produced by amateur actors and denoised after recording. nEMO (Christop, 2024)

is a Polish corpus of sentence-level, simulated emotional speech recorded by nine professional actors; although it originally provides six emotion categories, only those shared across all three corpora were retained. URDU-Dataset (Latif et al., 2018) consists of spontaneous emotional speech excerpts drawn from television talk shows and, in contrast to the other two corpora, captures naturally occurring rather than acted emotion. Taken together, these corpora constitute a deliberately heterogeneous benchmark that varies simultaneously in language, elicitation method, and utterance structure.

Label harmonization

Because the corpora annotate emotions using different surface strings (for example, *anger* versus *angry*), the same underlying emotion would otherwise be treated as several distinct classes, encouraging the model to learn the source corpus rather than the emotional content. To avoid this, all annotations were mapped onto a common canonical label space (anger/angry → *angry*; happiness/happy → *happy*; sadness/sad → *sad*). The neutral category was deliberately excluded, as it was represented inconsistently across corpora: the Turkish corpus provides a "calm" category rather than genuinely neutral speech, which would render a merged neutral class internally incoherent. Consequently, the study was restricted to the three emotions consistently present in all three corpora, namely *angry*, *happy*, and *sad*.

Audio preprocessing and segmentation

The three corpora differ substantially in utterance length. As shown in Figure 2, the Turkish utterances are word-level and short (median ≈ 0.95 s), whereas the Polish and Urdu recordings are sentence-level or spontaneous and considerably longer (medians of ≈ 2.4 s and ≈ 2.0 s, respectively), with maximum durations exceeding five seconds. If left unaddressed, such systematic differences would allow utterance duration, and by extension corpus identity, to act as a spurious proxy for emotion. To neutralize this confound, all recordings were resampled to 16 kHz and converted to mono, and then divided into non-overlapping, fixed one-second windows. Recordings longer than one second yielded multiple segments, providing an implicit form of data augmentation, whereas residual segments shorter than one second were zero-padded to the target length. Segments whose root-mean-square (RMS) energy fell below a fixed threshold, and which therefore consisted predominantly of silence, were discarded.

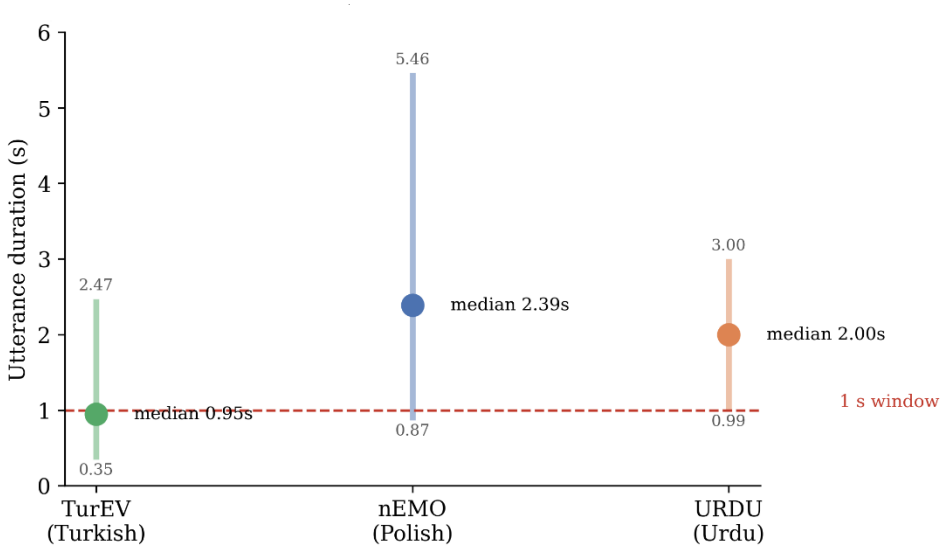


Figure 2. Utterance duration by corpus (median with min–max range).

Corpus and class balancing

Fixed-length segmentation introduced a pronounced imbalance: because the sentence-level Polish corpus produces more segments per recording, it dominated the resulting pool. To eliminate this bias, each (corpus × emotion) cell was randomly downsampled to an equal number of examples, namely 235 segments per cell. This single operation balances the data with respect to class and language simultaneously, yielding a final set of 3 emotions × 3 languages × 235 = 2,115 segments. The effect of this step is illustrated in Figure 3, which contrasts the class–language distribution before and after balancing.

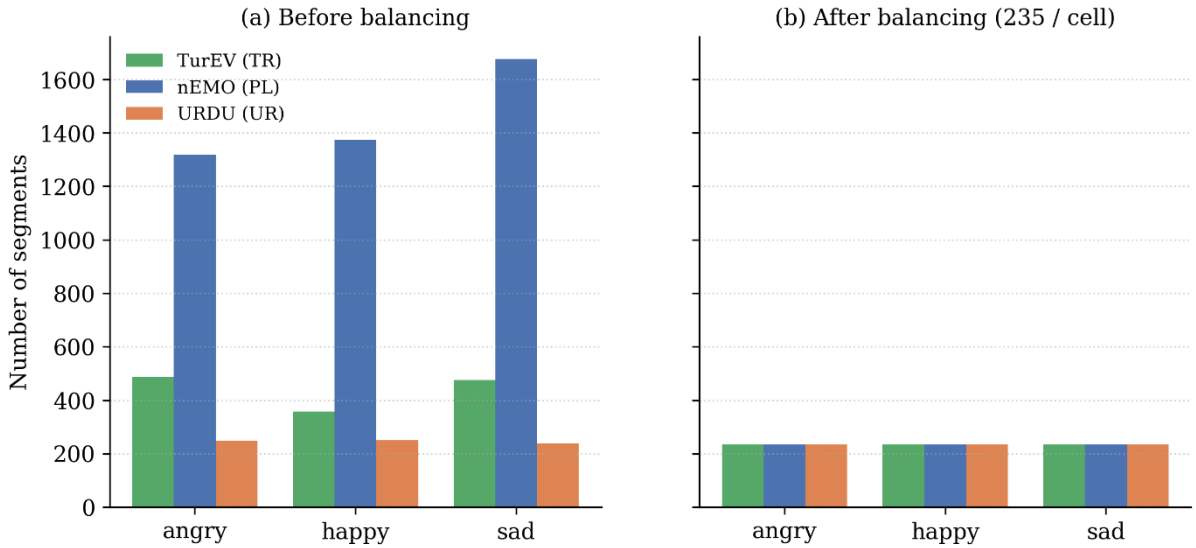


Figure 3. Class–language distribution before and after balancing.

Leakage-safe partitioning

Segmenting long recordings inevitably produces several segments that originate from the same source recording and therefore share the same speaker and acoustic environment. Allocating such segments to both the training and test sets would expose the model to test examples that closely resemble training examples, thereby inflating the reported performance through data leakage. To prevent this, partitioning was performed at the level of the original recording, so that all segments derived from a given recording were assigned exclusively to one side of the split. A stratified, group-based scheme (StratifiedGroupKFold) was used to preserve class balance while enforcing this grouping constraint, and the absence of any recording shared between the two sets was verified programmatically. An approximate 80% / 20% train–test ratio was targeted.

Model architecture and fine-tuning

The classification backbone was wav2vec2-XLS-R-300M (Babu et al., 2022), whose large-scale multilingual pretraining spans all three study languages. During fine-tuning, the convolutional feature encoder was kept frozen while the transformer layers and the classification head were updated, a standard and stabilizing practice for wav2vec2-family models. Optimization used a batch size of 4 with a gradient accumulation factor of 2 (yielding an effective batch size of 8), a learning rate of 1×10^{-5}, a warm-up ratio of 0.1, and 10 training epochs. Gradient checkpointing was enabled to reduce memory consumption, and bf16 mixed-precision training was employed for numerical stability. The final model was selected as the checkpoint achieving the highest validation macro-F1.

Evaluation protocol

As the evaluation set is balanced across classes, performance is summarized primarily through overall accuracy and macro-averaged F1, complemented by per-class precision, recall, and F1 and by a confusion matrix. To characterize the model's multilingual behavior, test performance is additionally disaggregated by corpus. Finally, as a preliminary point of comparison, a four-class configuration that additionally included the neutral category was trained using a smaller, English-pretrained backbone (wav2vec 2.0 base; Baevski et al., 2020).

4. Results and Discussion

The proposed configuration (XLS-R-300M, three classes) achieved an overall accuracy of 90.9% and a macro-F1 of 0.909 on the test set. Per-class results are reported in Table 1.

Table 1. Per-class performance (XLS-R-300M, three classes).

Class	Precision	Recall	F1	Support
Angry	0.912	0.918	0.915	146
Happy	0.908	0.838	0.872	142

Class	Precision	Recall	F1	Support
Sad	0.908	0.977	0.941	131
Macro avg.	0.909	0.911	0.909	419

Across the three classes, the highest performance was obtained for the *sad* class (F1 = 0.941) and the lowest for the *happy* class (F1 = 0.872). The confusion matrix in Figure 4 indicates that most errors originate from the *happy* class, with some happy segments misclassified as *angry* and others as *sad*. This pattern is consistent with happiness spanning both high-arousal instances, which acoustically resemble anger, and low-arousal ones. In contrast, sad segments were almost never confused with angry ones, as expected given the pronounced difference in arousal between these two emotions.

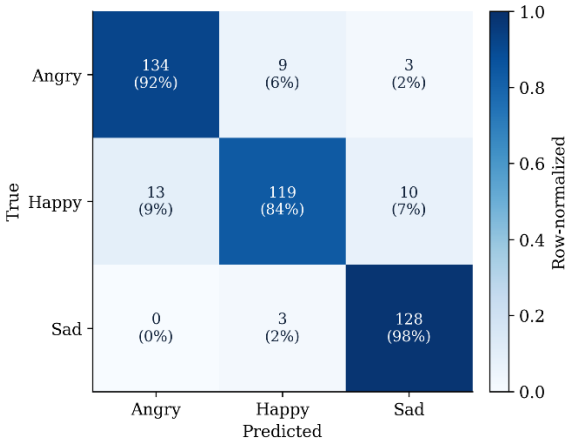


Figure 4. Row-normalized confusion matrix on the test set.

Table 2 reports macro-F1 disaggregated by corpus. An important methodological caveat must be emphasized: these scores correspond to a model in which all three languages are present in the training set, and therefore reflect in-domain performance rather than genuine cross-lingual transfer.

Table 2. Per-corpus macro-F1 (in-domain)

Corpus (Language)	Macro-F1	Support
nEMO (Polish)	0.927	141
URDU (Urdu)	0.949	137
TurEV (Turkish)	0.849	141

A notable observation is that the Turkish corpus yields the lowest performance despite being represented in training. A plausible explanation is that TurEV-DB comprises word-level utterances that are, in terms of duration, the shortest in the study (median ≈ 0.95 s); shorter segments carry less prosodic context than sentence-level or spontaneous excerpts, making emotion discrimination comparatively harder. This suggests that, in multilingual setups combining corpora with different utterance structures, performance depends not only on language but also on recording condition and utterance structure.

For comparison, a preliminary four-class configuration (wav2vec 2.0 base, including neutral) yielded a macro-F1 of 0.882. In that setting, the low precision of the neutral class (0.763), together with the confusion matrix, indicated that the model routed ambiguous examples into neutral, effectively turning it into a catch-all class; removing neutral eliminated this behavior. It should be noted, however, that the difference between the two configurations is confounded by two simultaneous changes — the backbone model and the number of classes — and thus cannot be attributed to a single factor.

Overall, these results indicate that a multilingually pretrained backbone can be fine-tuned into a strong three-class emotion classifier across Turkish, Polish, and Urdu, provided that label harmonization, corpus and class balancing, and leakage-safe evaluation are handled explicitly. At the same time, the per-corpus breakdown makes clear that the reported figures characterize in-domain behavior, and that utterance structure remains an influential factor alongside language.

5. Conclusion

This study combined emotional speech corpora from three languages (Turkish, Polish, and Urdu) within a common label space and fine-tuned a multilingually pretrained model (XLS-R-300M) to distinguish

three basic emotions (*angry*, *happy*, *sad*). The macro-F1 of 0.909 on a balanced test set demonstrates that multilingual pretrained representations can achieve strong emotion recognition performance even with limited and heterogeneous data.

Beyond the reported accuracy, the principal contribution of this work is methodological: it explicitly addresses pitfalls that are frequently overlooked in multilingual SER, namely cross-corpus label harmonization, the elimination of utterance-duration differences through uniform windowing, the simultaneous balancing of corpus and class, and — most importantly — the prevention of segment-level data leakage through group-based splitting. Each of these steps is essential for results that are realistic and reproducible.

Several limitations should be acknowledged. The per-corpus results reflect in-domain rather than cross-lingual transfer performance; the balanced set is relatively small (2,115 segments); classification is performed at the one-second segment level without utterance-level aggregation; and the corpora mix acted and spontaneous recordings, leaving recording-condition heterogeneity as a residual source of variability.

As future work, the most natural extension is a leave-one-language-out protocol — training on two languages and testing on the third — to quantify genuine cross-lingual transfer. Utterance-level aggregation, data-augmentation techniques, and a broader emotion set are further directions for improving both performance and generalizability.

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ACCURACY IS NOT ENOUGH: AN EFFICIENCY-AWARE COMPARISON OF CNN ARCHITECTURES FOR GAN-GENERATED FACE DETECTION

DOĞRULUK TEK BAŞINA YETERLİ DEĞİLDİR: GAN TARAFINDAN ÜRETİLEN YÜZLERİN TESPİTİNDE CNN MİMARİLERİNİN VERİMLİLİK ODAKLI KARŞILAŞTIRILMASI

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Abstract
The rapid advancement of generative models, particularly Generative Adversarial Networks and diffusion models, has made it possible to synthesize human faces that are visually indistinguishable from real photographs, raising serious concerns about misinformation, impersonation, and the erosion of trust in visual media. Reliable automated detection of such synthetic faces has therefore become an urgent research problem, and convolutional neural networks combined with transfer learning have emerged as the dominant approach. However, the many available CNN architectures are usually studied in isolation and under differing datasets and protocols, making it difficult to determine which backbone is most suitable when both accuracy and computational efficiency matter. This paper presents a controlled comparative study of five widely used ImageNet-pretrained architectures ResNet-18, ResNet-50, DenseNet-121, MobileNetV2, and EfficientNet-B0 for binary real/fake face classification on the public RVF10K dataset, whose real faces come from the Flickr-Faces-HQ dataset and whose fake faces are generated by StyleGAN. All models are trained and evaluated under an identical pipeline, including a freeze-then-fine-tune transfer-learning schedule, shared data augmentation, the Adam optimizer, and early stopping, and are assessed using accuracy, precision, recall, F1-score, and ROC–AUC together with efficiency indicators (parameter count and training time). Experimental results show that every model exceeds 97% accuracy with ROC–AUC above 0.997; ResNet-50 achieves the highest accuracy (99.53%) but is by far the largest model, whereas EfficientNet-B0 and MobileNetV2 attain nearly identical accuracy at a small fraction of the parameters and training cost. Notably, model size is found to be a poor predictor of detection accuracy, underscoring that architectural design is more decisive than raw capacity for practical GAN-generated face detection.
Keywords: Synthetic Image Detection, GAN-Generated Images, Deepfake Detection, Transfer Learning, Model Comparison, Image Forensics.

Özet
Üretici modellerin, özellikle Üretici Çekişmeli Ağların (Generative Adversarial Networks, GAN) ve difüzyon modellerinin hızla gelişmesi, gerçek fotoğraflardan görsel olarak ayırt edilemeyen sentetik insan yüzlerinin üretilmesini mümkün hâle getirmiştir. Bu durum, yanlış bilgilendirme, kimliğe bürünme ve görsel medyaya duyulan güvenin zedelenmesi gibi ciddi endişeleri beraberinde getirmektedir. Bu nedenle, söz konusu sentetik yüzlerin güvenilir ve otomatik bir şekilde tespit edilmesi acil bir araştırma problemi hâline gelmiş; transfer öğrenme ile birlikte kullanılan evrişimsel sinir ağları (CNN) ise bu alandaki baskın yaklaşımlardan biri olmuştur.
Bununla birlikte, mevcut çok sayıdaki CNN mimarisi genellikle birbirinden bağımsız olarak ve farklı veri kümeleri ile deneysel protokoller altında incelenmektedir. Bu durum, hem doğruluğun hem de hesaplama verimliliğinin önemli olduğu senaryolarda hangi omurga mimarisinin en uygun olduğunu belirlemeyi zorlaştırmaktadır. Bu çalışma, kamuya açık RVF10K veri kümesi üzerinde ikili gerçek/sahte yüz sınıflandırması gerçekleştirmek amacıyla, ImageNet üzerinde önceden eğitilmiş ve yaygın olarak kullanılan beş mimariyi — ResNet-18, ResNet-50, DenseNet-121, MobileNetV2 ve EfficientNet-B0 —

kontrollü bir karşılaştırmalı çalışma kapsamında incelemektedir. Veri kümesindeki gerçek yüzler Flickr-Faces-HQ veri kümesinden, sahte yüzler ise StyleGAN kullanılarak oluşturulmuştur.
Tüm modeller, karşılaştırmanın adil olmasını sağlamak amacıyla aynı deneysel işlem hattı kullanılarak eğitilmiş ve değerlendirilmiştir. Bu kapsamda, dondurma ve ardından ince ayar (fine-tuning) aşamalarından oluşan bir transfer öğrenme stratejisi, ortak veri artırma işlemleri, Adam optimizasyon algoritması ve erken durdurma (early stopping) uygulanmıştır. Modeller; doğruluk (accuracy), kesinlik (precision), duyarlılık (recall), F1-skoru ve ROC–AUC metriklerinin yanı sıra parametre sayısı ve eğitim süresi gibi verimlilik göstergeleri kullanılarak değerlendirilmiştir.
Deneysel sonuçlar, tüm modellerin %97'nin üzerinde doğruluk ve 0,997'nin üzerinde ROC–AUC değerine ulaştığını göstermektedir. ResNet-50, %99,53 doğruluk ile en yüksek başarıyı elde etmiş, ancak açık ara en büyük model olmuştur. Buna karşılık, EfficientNet-B0 ve MobileNetV2, çok daha az sayıda parametre ve daha düşük eğitim maliyetiyle ResNet-50'ye neredeyse eşdeğer doğruluk seviyelerine ulaşmıştır. Özellikle, model boyutunun tespit doğruluğunun zayıf bir belirleyicisi olduğu görülmüştür. Bu bulgu, pratik GAN tarafından üretilen yüz tespitinde başarının yalnızca modelin ham kapasitesine değil, mimari tasarımın daha belirleyici olduğuna işaret etmektedir.
Anahtar kelimeler: Sentetik Görüntü Tespiti, GAN Tarafından Üretilen Görüntüler, Deepfake Tespiti, Transfer Öğrenme, Model Karşılaştırması, Görüntü Adli İncelemesi

THE ROLE OF STORYTELLING IN DESTINATION BRANDING: THE CASE OF ERMENEK

DESTİNASYON MARKALAŞMASINDA HİKÂYELEŞTİRMENİN ROLÜ: ERMENEK ÖRNEĞİ

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Abstract
The way in which the natural, historical, and cultural values of destinations are communicated to visitors plays a crucial role in transforming these resources into meaningful tourism experiences. Contemporary destination branding encompasses not only the promotion of tourist attractions but also the communication of a destination's distinctive identity, local culture, and narratives of the past. This study aims to examine the contribution of storytelling to destination branding by exploring the historical, natural, and cultural values of Ermenek, a district of Karaman, Türkiye. A qualitative research approach was adopted, and semi-structured interviews were conducted with twelve participants. The collected data were analyzed using thematic analysis.
The findings indicate that Ermenek's destination identity is shaped by a diverse range of elements, including the history of the Karamanoğulları, natural landscapes, the Ermenek Dam Lake, Zeyve Bazaar, Yörük culture, local gastronomic values, and the district's distinctive microclimatic characteristics. Participants emphasized that attractions such as Ayhatun Cave, canyons, the old bazaar, historical structures, and local culinary products should receive greater attention in tourism promotion. The interviews also revealed various local narratives concerning the legend of the Karaman sheep, the Karamanoğulları and Ottoman periods, Ayhatun Cave, Karamanoğlu Mehmet Bey, historical sites, hospitality, and gift-giving traditions. All twelve participants stated that these stories are not sufficiently incorporated into existing tourism promotional activities. They noted that current promotional efforts rely predominantly on visual content, while the historical and cultural narratives associated with places remain largely underrepresented. Furthermore, some local narratives are at risk of disappearing from collective memory due to their limited documentation in written sources.Overall, the findings demonstrate that Ermenek possesses substantial storytelling potential; however, this potential has not yet been transformed into a comprehensive destination brand narrative. The use of local stories through short videos, social media, reenactments, thematic routes, and digital applications is therefore recommended.
Keywords: Destination Branding, Storytelling, Destination Identity, Local Stories, Ermenek

Özet
Destinasyonların sahip olduğu doğal, tarihî ve kültürel değerlerin turizm açısından anlam kazanmasında bu değerlerin ziyaretçilere nasıl aktarıldığı önemli bir rol oynamaktadır. Günümüzde destinasyon markalaşması yalnızca turistik çekiciliklerin tanıtılmasını değil destinasyonun özgün kimliğinin, yerel kültürünün ve geçmişine ilişkin anlatıların ziyaretçilere aktarılmasını da kapsamaktadır. Bu çalışmanın amacı Karaman'ın Ermenek ilçesinin sahip olduğu tarihî, doğal ve kültürel değerlerin hikâyeleştirme yoluyla destinasyon markalaşmasına katkısını ortaya koymaktır. Araştırmada nitel araştırma yöntemi benimsenmiş ve on iki katılımcıyla yarı yapılandırılmış görüşmeler gerçekleştirilmiştir. Elde edilen veriler tematik analiz yöntemiyle değerlendirilmiştir. Bulgular Ermenek'in destinasyon kimliğinin Karamanoğulları tarihi, doğal güzellikleri, baraj gölü, Zeyve Pazarı, Yörük kültürü, gastronomik değerleri ve mikroklimatik özellikleri gibi çok sayıda unsurdan oluştuğunu göstermektedir. Katılımcılar ayrıca Ayhatun Mağarası, kanyonlar, eski çarşı, tarihî yapılar ve yerel gastronomik değerlerin daha fazla öne çıkarılması gerektiğini belirtmiştir. Görüşmelerde Karaman'ın koyunu efsanesi, Karamanoğulları ve Osmanlı dönemine ilişkin anlatılar, Ay hatun Mağarası, Karamanoğlu Mehmet Bey, tarihî mekânlar,

misafirperverlik ve hediyeleşme gelenekleri gibi çeşitli yerel hikâyeler ortaya çıkmıştır. On iki katılımcının tamamı bu hikâyelerin mevcut Ermenek turizm tanıtımlarında yeterince kullanılmadığını ifade etmiştir. Katılımcılar tanıtımların ağırlıklı olarak görsel unsurlara dayandığını ve mekânların arkasındaki tarihî ve kültürel anlatıların yeterince aktarılmadığını vurgulamıştır. Ayrıca bazı yerel anlatıların yazılı kaynaklara yeterince aktarılmaması nedeniyle yöre halkının hafızasında kaybolma riski taşıdığı belirtilmiştir. Sonuç olarak Ermenek'in güçlü bir hikâyeleştirme potansiyeline sahip olduğu, ancak bu potansiyelin bütüncül bir destinasyon marka anlatısına yeterince dönüştürülemediği belirlenmiştir. Hikâyelerin kısa videolar, sosyal medya, canlandırmalar, tematik rotalar ve dijital uygulamalar aracılığıyla kullanılması önerilmektedir.

Anahtar kelimeler: Destinasyon Markalaşması, Hikâyeleştirme, Destinasyon Kimliği, Yerel Hikâyeler, Ermenek

KAYDIRIRKEN KAYBOLMAK: ÇOK BOYUTLU BİR DİJİTAL BAĞIMLILIK ÖLÇEĞİNİN GELİŞTİRİLMESİ VE GEÇERLİLİK ÇALIŞMASI VE RUH SAĞLIĞIYLA İLİŞKİLERİ

LOST WHILE SCROLLING: DEVELOPMENT AND VALIDATION OF A MULTIDIMENSIONAL DIGITAL ADDICTION SCALE AND ITS ASSOCIATIONS WITH MENTAL HEALTH

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Abstract
Digital addiction, characterized by loss of control, compulsive engagement, and functional impairment associated with smartphone and social media use, has become an increasing focus of psychological research. This study proposed and tested a multidimensional higher-order conceptualization of digital addiction encompassing five behavioral dimensions: phone attachment, digital interference, compulsive scrolling, fear of missing out (FoMO), and social media overuse. A cross-sectional survey was conducted with 494 Turkish participants (58.2% female; M age = 25.56, SD = 11.22, range = 14–61). Exploratory and confirmatory factor analyses supported a five-factor structure loading onto a single higher-order construct, with excellent model fit. Digital addiction was positively associated with psychological distress, including depression, anxiety, anger, sleep disturbance, obsessive-compulsive symptoms, dissociation, impulsivity, and borderline personality features, and negatively associated with psychological resources, including self-esteem, purpose in life, and religiosity. Regression analyses indicated that distress variables explained roughly twice as much variance in digital addiction (32.1%) as psychological resources did (16.8%), with depression emerging as the strongest unique correlate.

Everyday smartphone behaviors, specifically carrying the phone in hand rather than in a pocket or bag, and placing it on the dining table during meals, were associated with higher digital addiction and poorer psychological functioning, supporting their potential use as observable behavioral markers. Approximately 10% of participants displayed serious digital addiction. These findings support conceptualizing digital addiction as a coherent, multidimensional construct embedded within a broader network of psychological distress, resources, and everyday behavioral patterns, with implications for assessment and preventive intervention.
Keywords: digital addiction; smartphone use; social media; psychological distress

Özet

Akıllı telefon ve sosyal medya kullanımına bağlı kontrol kaybı, kompulsif kullanım ve işlevsellikte bozulma ile karakterize edilen dijital bağımlılık, psikoloji araştırmalarında giderek daha fazla ilgi gören bir konu hâline gelmiştir. Bu çalışmada dijital bağımlılığın; telefona bağlılık, dijital aksama, kompulsif kaydırma, gelişmeleri kaçırma korkusu (FoMO) ve aşırı sosyal medya kullanımı olmak üzere beş davranışsal boyutu kapsayan çok boyutlu ve üst düzey bir yapı olarak kavramsallaştırılması önerilmiş ve sınanmıştır. Kesitsel araştırma, 494 Türk katılımcıyla (%58,2 kadın; yaş Ort. = 25,56, SS = 11,22, aralık = 14–61) gerçekleştirilmiştir. Açımlayıcı ve doğrulayıcı faktör analizleri, tek bir üst düzey yapıya yüklenen beş faktörlü modeli desteklemiş ve modelin mükemmel uyum gösterdiğini ortaya koymuştur. Dijital bağımlılık; depresyon, kaygı, öfke, uyku bozukluğu, obsesif-kompulsif belirtiler, dissosiyasyon, dürtüsellik ve borderline kişilik özelliklerini içeren psikolojik sıkıntı göstergeleriyle pozitif; benlik saygısı, yaşam amacı ve dindarlığı içeren psikolojik kaynaklarla ise negatif yönde ilişkili bulunmuştur. Regresyon analizleri, psikolojik sıkıntı değişkenlerinin dijital bağımlılıktaki varyansın %32,1'ini açıklarken psikolojik kaynakların %16,8'ini açıkladığını; dolayısıyla sıkıntı değişkenlerinin yaklaşık iki kat daha fazla açıklayıcı güce sahip olduğunu göstermiştir. Depresyon, dijital bağımlılıkla en güçlü özgün ilişkiye sahip değişken olarak öne çıkmıştır. Gündelik akıllı telefon kullanım davranışlarından özellikle telefonu cepte veya çantada taşımak yerine elde taşımak ve yemek sırasında telefonu masanın üzerine koymak, daha yüksek dijital bağımlılık ve daha olumsuz psikolojik işlevsellikle ilişkili bulunmuştur. Bu bulgular, söz konusu davranışların gözlenebilir davranışsal göstergeler olarak kullanılabileceğine işaret etmektedir. Katılımcıların yaklaşık %10'unda ciddi düzeyde dijital bağımlılık gözlenmiştir. Bu bulgular, dijital bağımlılığın psikolojik sıkıntılar, psikolojik kaynaklar ve gündelik davranış örüntülerinden oluşan daha geniş bir ağ içinde yer alan bütünlüklü ve çok boyutlu bir yapı olarak kavramsallaştırılmasını desteklemekte; ayrıca değerlendirme ve önleyici müdahaleler açısından önemli çıkarımlar sunmaktadır.
Anahtar Kelimeler: dijital bağımlılık; akıllı telefon kullanımı; sosyal medya; psikolojik stres

BIOGENIC NANOPARTICLES FOR MANAGING PLANT DNA VIRUSES AND THEIR INSECT VECTORS

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Abstract
Plant DNA viruses, particularly begomoviruses and badnaviruses, remain difficult to manage because systemic infection is established rapidly and many economically important species depend on efficient insect transmission. Biogenic nanoparticles offer a complementary strategy in which nanoscale materials are produced or functionalized using plants, microorganisms, or bio-derived polymers rather than exclusively chemical routes. Their potential extends beyond direct antiviral activity to induction of host defenses, protection and delivery of nucleic-acid-based antivirals, sensitive virus detection, and suppression of insect vectors. This review synthesizes recent evidence from 2022-2026 on biogenic nanoparticles for management of plant DNA viruses and their vectors. Current evidence is strongest for green-synthesized silver nanoparticles and related nanoformulations against whiteflies, whereas direct studies on DNA viruses are fewer. Chitosan nanoparticles have shown notable activity against banana streak virus, and nano-enabled delivery and diagnostic platforms provide additional routes for managing begomovirus diseases. Despite this promise, translation to field use requires reproducible particle characterization, transmission-focused efficacy trials, crop and non-target safety assessment, environmental fate studies, and clear regulatory standards. An integrated strategy combining vector suppression, host defense priming, sequence-specific antiviral delivery, and early diagnosis is likely to be the most realistic pathway for deployment.
Keywords: biogenic nanoparticles; plant DNA viruses; begomoviruses; banana streak virus; whitefly; Bemisia tabaci; nanophytovirology.

1. Introduction

Plant DNA viruses are disproportionately important in tropical and subtropical agriculture because many are efficiently transmitted by phloem-feeding insects and can establish persistent epidemics in high-value crops. Begomoviruses in the family Geminiviridae are single-stranded DNA viruses transmitted mainly by members of the *Bemisia tabaci* whitefly complex, and their rapidly evolving plant-vector-virus interactions complicate durable control (Naveed et al., 2023; Morin et al., 2024; Biswas and Mandal, 2025). DNA pararetroviruses such as banana streak virus (BSV) add a different management problem because infection may be associated with persistent planting material and complex host responses. Conventional management therefore relies on resistant cultivars, clean planting material, sanitation, insecticides, and vector exclusion, yet these measures can be undermined by resistance-breaking virus variants, insecticide resistance, reinvasion by mobile vectors, and incomplete availability of host resistance.

Nanotechnology is increasingly examined as an additional layer of plant-virus management. Recent reviews describe nanoparticles as antiviral agents, defense elicitors, diagnostic components, and carriers for RNA interference or other sequence-specific molecules (Dutta et al., 2022; Singh et al., 2022; Warghane et al., 2024; Rajeshkumar et al., 2025; Vasquez-Gutierrez et al., 2025). The biogenic approach

is particularly attractive because nanoparticles can be synthesized with plant extracts, fungi, bacteria, or biologically derived macromolecules, potentially reducing dependence on harsh reducing and capping reagents. However, "green" or "biogenic" should not be treated as synonymous with harmless; biological activity and environmental behavior still depend on particle composition, size, coating, concentration, dissolution, and exposure route.

A central challenge is that the evidence base is uneven. Broad nanoparticle-plant virus research is expanding, but direct experiments targeting DNA plant viruses remain relatively scarce compared with studies of RNA viruses or fungal and bacterial pathogens. At the same time, strong progress has been made in nano-enabled diagnostics and insect-vector suppression, creating an opportunity to intervene before or during transmission rather than only after systemic infection is established (Mishra et al., 2025; Kalu et al., 2026). Accordingly, this review focuses on the recent 2022-2026 literature and evaluates biogenic nanoparticles through four linked functions: direct antiviral action, stimulation or delivery of host antiviral responses, suppression of insect vectors, and integration into practical disease-management systems.

2. Biogenic Nanoparticle Platforms and Antiviral Mechanisms

Biogenic nanoparticles encompass inorganic particles produced using biological reducing and stabilizing systems as well as bio-derived nanocarriers such as chitosan. Plant-mediated synthesis commonly exploits polyphenols, flavonoids, sugars, proteins, and other metabolites that reduce metal ions and simultaneously cap the resulting particles; microbial synthesis uses extracellular or intracellular metabolites from bacteria and fungi for related purposes (Nguyen et al., 2022; Omran and Baek, 2022; Nguyen et al., 2023). Silver nanoparticles (AgNPs) remain the most studied green nanomaterial in crop protection, but ZnO, Cu/CuO, MgO, iron oxides, gold, and hybrid nanocomposites are also being developed. Bio-derived polymers provide another route because their surfaces can be functionalized, loaded with nucleic acids or active compounds, and formulated for foliar delivery (Wasule et al., 2024). Recent reviews focused specifically on bacterial- and fungal-mediated routes further demonstrate how microbial metabolism can support eco-friendly nanoparticle synthesis and phytopathogen management (Ali et al., 2024; Aasim et al., 2025).

Several mechanisms are relevant to plant-virus management. First, nanoparticles may directly interact with viral particles, capsid proteins, or nucleic acids, potentially reducing stability, replication, movement, or successful establishment of infection. Metal-based particles can also generate reactive oxygen species or release ions, although the same chemistry that damages pathogens can become phytotoxic at excessive exposure (Warghane et al., 2024). Second, nanoparticles may prime plant immunity by altering redox signaling, antioxidant systems, defense enzymes, and salicylic acid-, jasmonic acid-, or ethylene-associated pathways. Such priming is attractive for viruses because the target is the host response rather than a single viral enzyme, but its magnitude is highly dependent on dose, crop species, particle characteristics, and application timing (Saied et al., 2026; Parihar et al., 2026). Third, nanocarriers can protect unstable antiviral cargo. Double-stranded RNA, small RNAs, peptides, or other bioactive molecules are readily degraded on leaf surfaces or in the environment; nanoscale carriers can improve adhesion, persistence, cellular uptake, and controlled release. This concept is particularly relevant to DNA viruses because sequence-specific RNA silencing can target viral transcripts even though the viral genome itself is DNA (Rajeshkumar et al., 2025). Fourth, nanoparticle-enabled sensing can increase the sensitivity or portability of virus detection, supporting earlier roguing and vector management before visible symptoms become widespread. A recent plant-virus-focused synthesis similarly identifies nanocarrier-mediated RNA delivery as a central route for overcoming dsRNA instability and uptake limitations, while emphasizing formulation-to-field validation as the critical translational gap (Ali, 2026).

Biogenic synthesis adds sustainability advantages, but reproducibility remains a technical bottleneck. Extract composition varies with species, tissue, season, extraction conditions, and metabolite profile, which can change particle size and surface chemistry between batches. For this reason, recent assessments emphasize full characterization of size distribution, morphology, zeta potential, coating chemistry, release behavior, and stability rather than labeling a preparation simply as "green" (Salam et al., 2026; Kalu et al., 2026). Mechanistic interpretation therefore requires linking biological outcomes to well-defined physicochemical properties.

3. Applications Against Plant DNA Viruses

The direct evidence for biogenic nanoparticles against plant DNA viruses is promising but still narrow. The clearest recent example is BSV, a DNA pararetrovirus of banana. Abdelbaset et al. (2024) reported that foliar chitosan nanoparticles substantially reduced BSV colonization and disease development. Under their experimental conditions, a 200 mg L−1 pre-inoculation treatment reduced disease incidence by 75% and disease severity by 95.3%, while higher pre- and post-inoculation concentrations produced complete suppression of the measured disease-incidence and severity endpoints. These results are important because they demonstrate that a bio-derived nanoparticle can alter the outcome of a DNA-virus infection *in planta* rather than functioning only as an insecticide or diagnostic material.

For begomoviruses, the recent literature is more developed conceptually than experimentally. Reviews of nanophytovirology identify direct nanoparticle-virus interactions, host defense induction, and nano-assisted delivery of RNA-silencing molecules as the principal antiviral routes (Dutta et al., 2022; Singh et al., 2022; Warghane et al., 2024). This framework is especially relevant to tomato yellow leaf curl disease and related begomovirus complexes because viral transcripts, replication-associated proteins, movement functions, or conserved genome regions can be targeted by sequence-specific molecules. Nanocarrier protection may extend persistence of such molecules on leaves and facilitate entry into plant tissues, addressing two major limitations of naked RNA-based sprays (Rajeshkumar et al., 2025; Vasquez-Gutierrez et al., 2025; Mishra et al., 2025). Nevertheless, recent reviews also make clear that robust field-scale demonstrations against DNA viruses are not yet proportional to the number of proposed nano-delivery concepts. Diagnosis is therefore an important complementary application. Devika et al. (2024) demonstrated nano-PCR for early detection of tomato leaf curl virus, illustrating how nanomaterials can enhance diagnostic sensitivity in a DNA-virus pathosystem. Earlier and more sensitive detection does not itself cure an infected plant, but it can materially improve integrated management by enabling rapid removal of inoculum sources, screening of nursery stock, and earlier vector-control decisions. Current nanotechnology reviews similarly position high-sensitivity detection as part of a disease-management continuum rather than a separate laboratory activity (Salam et al., 2026; Kalu et al., 2026).

The most defensible interpretation is therefore that biogenic nanoparticles have demonstrated proof of principle against at least one important plant DNA virus and possess credible mechanisms for broader use, but evidence should not be generalized across all Geminiviridae, Nanoviridae, or Caulimoviridae. Future experiments should quantify viral DNA, transcript abundance, symptom severity, yield, and transmission to recipient plants while comparing prophylactic and post-infection applications. Such designs would distinguish true antiviral activity from temporary symptom mitigation or nonspecific growth promotion.

4. Suppression of Insect Vectors and Virus Transmission

For many plant DNA viruses, vector management is an antiviral intervention because infection risk depends on vector abundance, feeding behavior, acquisition, retention, and inoculation. Begomoviruses are tightly associated with *B. tabaci*, and recent molecular reviews show that successful transmission is shaped by reciprocal interactions among the plant, virus, whitefly, and whitefly-associated factors (Naveed et al., 2023; Morin et al., 2024; Zhao et al., 2025; Biswas and Mandal, 2025). A nanoparticle that reduces vector survival, development, settling, or feeding could therefore decrease primary or secondary spread even without directly contacting the virus.

Biogenic AgNPs provide the strongest recent vector-control evidence. Shahid et al. (2022) evaluated an *Azadirachta indica*-mediated silver nanoformulation against *B. tabaci* and reported substantial biocidal activity, supporting plant-extract-based synthesis as a route to whitefly control. Bhadani et al. (2022) used extracellular metabolites of *Beauveria bassiana* to biosynthesize AgNPs and demonstrated concentration- and exposure-dependent toxicity to whiteflies. These studies are particularly relevant because *B. tabaci* transmits numerous begomoviruses affecting tomato, cotton, cassava, pepper, legumes, and other crops. In a related whitefly system, Trujillo et al. (2025) produced highly stable rosemary-mediated silver nanocomposites and reported approximately 98% average mortality of naturally occurring *Trialeurodes vaporariorum* on greenhouse tomato after 10 days. Although *T. vaporariorum* is not the principal vector of begomoviruses, the result strengthens the broader case for green silver nanomaterials as whitefly-active formulations. The likely insecticidal mechanisms are multifactorial. Recent synthesis of AgNP toxicology describes disruption of membrane permeability,

oxidative stress and reactive oxygen species production, interference with enzymes and proteins, impairment of DNA replication, and developmental abnormalities (Martínez-Cisterna et al., 2024). Biogenic coatings may additionally influence adhesion, uptake, persistence, and compatibility with plant surfaces. However, high vector mortality should not automatically be equated with proportional reduction in virus transmission. Whiteflies can acquire and inoculate virus before death, and sublethal exposure could alter movement or feeding in ways that either decrease or, under some circumstances, redistribute transmission risk.

Accordingly, vector-focused nanoparticle trials should include epidemiological endpoints. Useful measurements include probing behavior, acquisition access period, inoculation efficiency, latent or retention dynamics where relevant, numbers of newly infected plants, and epidemic progress, in addition to LC50 or mortality. Combining nanoparticle-based vector suppression with host defense priming or sequence-specific antiviral cargo could provide two independent barriers to infection, an approach consistent with current nano-enabled plant-virus management frameworks (Mishra et al., 2025). Such combinations may also reduce reliance on repeated conventional insecticide applications if efficacy and selectivity can be demonstrated under field conditions.

5. Field Translation, Biosafety and Research Priorities

The main barrier to adoption is no longer the absence of plausible mechanisms but the lack of standardized evidence linking nanoparticle properties to durable field performance. Biogenic synthesis can reduce hazardous chemical inputs, yet batches generated with crude plant or microbial extracts may differ in size, surface coating, aggregation state, ion release, and biological potency (Omran and Baek, 2022; Nguyen et al., 2023). Minimum characterization should therefore include particle size distribution, morphology, zeta potential, chemical composition, capping molecules, storage stability, and behavior after dilution in realistic spray water. Without these data, efficacy cannot be reliably reproduced across laboratories or seasons (Wasule et al., 2024; Salam et al., 2026).

Safety evaluation must be equally specific. Nanoparticles that generate oxidative stress in vectors or pathogens may also affect crop cells, beneficial arthropods, soil microorganisms, aquatic organisms, or food-chain exposure. Recent assessments emphasize dose-dependent phytotoxicity, uncertainty concerning environmental persistence and transformation, and the need to study nanoparticle-microbiome-plant interactions under field conditions (Kalu et al., 2026; Parihar et al., 2026). Green synthesis may improve the toxicological profile in some cases, but it does not eliminate the need for residue, non-target, and chronic-exposure studies. This is particularly important for AgNPs because both particulate silver and released Ag^+ can contribute to biological effects (Martínez-Cisterna et al., 2024).

Efficacy testing also needs to move from mortality and symptom scores toward transmission-centered field endpoints. The encouraging whitefly control reported for green Ag-based formulations should be validated against virus-vector pairs of direct epidemiological importance, particularly *B. tabaci*-begomovirus systems, using realistic application intervals and environmental conditions (Trujillo et al., 2025). Likewise, the BSV-chitosan nanoparticle result warrants multisite validation, assessment of persistence, and measurement of viral load and yield responses. Nano-enabled delivery systems should be compared with unformulated cargo to demonstrate that the nanoparticle itself provides measurable gains in stability, uptake, dose efficiency, or duration (Vasquez-Gutierrez et al., 2025; Mishra et al., 2025).

A productive research pathway is an integrated “virus-vector-host” design. Candidate formulations should first be characterized physically and chemically, then screened for crop safety, antiviral or vector activity, and host-defense responses. The best candidates should subsequently be tested for reduction of plant-to-plant transmission and yield loss. Diagnostic tools can be integrated to detect low-titer infections and quantify treatment effects. Finally, regulatory development will require agreed definitions for nanoformulations, standardized ecotoxicological protocols, residue and exposure thresholds, and manufacturing quality control. Such steps would allow biogenic nanotechnology to progress from promising laboratory demonstrations to evidence-based components of integrated virus management.

6. Conclusion

Biogenic nanoparticles provide a multifunctional platform for managing plant DNA-virus diseases because they can act on the virus, the host, the vector, or the delivery of antiviral molecules. The strongest current evidence lies in green nanoparticle toxicity against whiteflies and in the demonstrated activity of chitosan nanoparticles against banana streak virus. For begomoviruses and other DNA-virus

groups, nano-enabled defense priming, nucleic-acid delivery, and sensitive diagnostics are scientifically credible but require more direct, transmission-focused validation. Future progress will depend on standardized synthesis and characterization, clear comparisons with non-nano controls, field trials measuring virus spread and yield, and rigorous assessment of crop, environmental, and non-target safety. The most practical role for biogenic nanoparticles is therefore not as a single replacement for existing control measures, but as a component of integrated management that combines early detection, vector suppression, host protection, and targeted antiviral delivery.

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THE RHIZOSPHERE MICROBIOME AS A BIOLOGICAL SHIELD AGAINST PLANT DISEASES

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Abstract
The rhizosphere microbiome is increasingly recognized as a biologically active shield that protects plants from soil-borne and aboveground pathogens. Rather than acting through a single mechanism, rhizosphere communities restrict pathogen invasion by occupying ecological niches, competing for nutrients, producing antimicrobial metabolites and lytic enzymes, modifying the chemical environment around roots, and priming systemic immune responses. Plants are active participants in this defense system. Root exudates and host genetic traits selectively recruit beneficial microorganisms, particularly after pathogen attack, creating a dynamic "cry-for-help" response that can reinforce disease resistance. Recent work has also moved from descriptive microbiome surveys toward causal approaches using disease-suppressive soils, microbial transplants, synthetic communities, metabolomics, metagenomics, and host-mediated microbiome engineering. This short review synthesizes advances published during 2022-2026, with emphasis on the ecological and molecular mechanisms underlying microbiome-mediated disease suppression, plant-guided recruitment of protective taxa, synthetic microbial communities, and translation to crop protection. Evidence increasingly supports the rhizosphere microbiome as an extension of plant immunity, but field consistency, formulation stability, host specificity, environmental context, and regulatory frameworks remain major barriers to agricultural deployment.
Keywords: rhizosphere microbiome; disease suppression; biological control; root exudates; disease-suppressive soil; synthetic microbial communities; induced systemic resistance

1. Introduction

The rhizosphere is the narrow, metabolically active zone of soil influenced by plant roots, where microbial population densities and biochemical interactions are markedly greater than in bulk soil. Its bacteria, fungi, archaea, protists, and viruses interact with one another and with the host plant, forming a dynamic interface that can determine whether an invading pathogen successfully establishes infection. Contemporary plant pathology therefore increasingly treats the plant and its associated microbiota as an integrated ecological unit rather than viewing immunity as a property of plant cells alone (Santoyo, 2022). Disease-suppressive microbiome research further supports this holobiont-level interpretation (Spooren et al., 2024). Recent syntheses describe the rhizosphere microbiome as an important determinant of disease resistance and a potential first line of defense against soil-borne pathogens (Andargie et al., 2023; Du et al., 2025).

The "biological shield" concept is supported by experiments showing that small differences in microbial community composition can precede major differences in disease outcome. In tomato challenged with Ralstonia solanacearum, rhizosphere community configurations predicted later bacterial wilt outcomes before clear differences in pathogen density were detectable, and several bacteria enriched in healthy plants reduced disease when reintroduced experimentally (Gu et al., 2022). Disease-suppressive soils

provide a broader ecological manifestation of the same phenomenon: susceptible plants can remain relatively healthy in the presence of a virulent pathogen because resident microbial communities restrict pathogen growth or infection (Spooren et al., 2024; Li et al., 2024). The defensive microbiome is not static. It is shaped by soil properties, plant genotype, developmental stage, root chemistry, pathogen pressure, agronomic management, and interactions among microbial kingdoms (Andargie et al., 2023; Liu et al., 2026). Field-oriented assessments in tomato further indicate that manipulation of rhizosphere communities through organic inputs and biological products can contribute to suppression of bacterial, fungal, and nematode diseases, although functional validation in field environments remains less developed than controlled-environment research (Obiazikwor et al., 2025). Recent demonstrations that defined rhizosphere communities can induce systemic resistance to foliar disease also extend the shield beyond the root zone itself (Rigerte et al., 2026). This review examines how the rhizosphere microbiome forms this protective barrier, how plants assemble it, and how microbiome-based disease suppression may be converted into reliable crop-protection technologies.

2. Mechanisms Underlying the Rhizosphere Biological Shield

Microbiome-mediated disease suppression emerges from multiple overlapping mechanisms. The most immediate is colonization resistance: a dense, metabolically active community occupies physical attachment sites and consumes limiting carbon, nitrogen, iron, and micronutrients before an invading pathogen can establish a sufficient population. Such resource competition is strengthened by high community diversity and complementary resource use, making pathogen invasion more difficult than in simplified or disrupted microbiomes (Du et al., 2025; Liu et al., 2026). Longitudinal tomato experiments support this ecological interpretation because healthy plants developed distinct community configurations containing protective taxa before bacterial wilt became visible (Gu et al., 2022).

Antibiosis provides a second protective layer. Rhizosphere bacteria such as *Bacillus*, *Pseudomonas*, and Streptomyces can produce lipopeptides, polyketides, non-ribosomal peptides, antibiotics, siderophores, volatile compounds, and hydrolytic enzymes. Fungi such as Trichoderma contribute mycoparasitism, competition, chitinases, and other antifungal activities. In suppressive soil challenged with *Fusarium solani*, *Bacillus* and *Trichoderma* acted as keystone antagonists; defined consortia containing these taxa markedly reduced pathogen sporulation and root-rot severity (Li et al., 2024). Likewise, maize root exudates recruited *Bacillus amyloliquefaciens* OR2-30, which suppressed Fusarium graminearum partly through lipopeptide production (Xie et al., 2022). Evidence from tomato also supports rhizosphere-associated Pseudomonas: *P. fluorescens* strains reduced Meloidogyne incognita root galling and improved tomato growth under greenhouse conditions (Ayub et al., 2024). A recent review of tomato Fusarium wilt likewise highlights *Pseudomonas*, *Bacillus*, and *Streptomyces* acting through antibiosis, resource competition, growth promotion, and host-defense activation (Tatar et al., 2025). The shield also acts through plant immunity. Beneficial rhizobacteria can prime induced systemic resistance, allowing distal tissues to respond faster or more strongly after pathogen attack without maintaining costly constitutive defense. This process commonly intersects with jasmonic acid, ethylene, salicylic acid, reactive oxygen species, defense enzymes, and transcriptional reprogramming (Du et al., 2025; Spooren et al., 2024). In 2026, defined bacterial SynComs derived from barley and wheat rhizospheres reduced powdery mildew growth on barley leaves while causing only subtle pre-infection transcriptional changes, consistent with immune priming rather than constitutive stress (Rigerte et al., 2026).

Community interactions are equally important. A protective phenotype often cannot be attributed to a single strain because facilitation, metabolite exchange, spatial organization, and cross-kingdom interactions generate emergent functions. Cross-kingdom bacterial-fungal SynComs were more effective than bacteria-only or fungi-only communities in suppressing tomato Fusarium wilt, linking disease control to both microbial interactions and host immune responses (Zhou et al., 2022). A 16-member bacterial community from grafted watermelon similarly protected ungrafted plants against *Fusarium oxysporum*, with *Pseudomonas*-associated functions and microbial synergy contributing to the effect (Qiao et al., 2024). Thus, the biological shield is best understood as a community-level ecological function integrating niche exclusion, antagonism, chemical competition, microbial cooperation, and immune activation rather than as the activity of a single “beneficial microbe” (Andargie et al., 2023).

3. Plant-Guided Recruitment and the Cry-for-Help Response

Plants actively influence rhizosphere assembly through root exudates containing sugars, amino acids, organic acids, phenolics, flavonoids, coumarins, hormones, and other metabolites. These compounds are nutrient sources but also function as selective signals that alter microbial chemotaxis, growth, biofilm formation, and competitive fitness. Consequently, root exudation provides a mechanism by which plants can enrich microorganisms with disease-suppressive traits (Santoyo, 2022; Spooren et al., 2024). The composition of exudates changes with genotype, developmental stage, nutrition, and biotic stress, allowing the host to reshape its microbial environment in response to changing threats (Andargie et al., 2023).

Recent studies provide direct evidence for pathogen-responsive recruitment. Following *Fusarium graminearum* infection, maize altered root exudation in a manner that enhanced recruitment of *B. amyloliquefaciens* OR2-30, which subsequently inhibited the pathogen (Xie et al., 2022). In *Panax notoginseng*, foliar infection modified root exudates and enriched rhizosphere *Trichoderma*, *Bacillus*, and *Streptomyces* while suppressing a soil-borne root-rot pathogen; metabolite amendments reproduced parts of this protective effect (Luo et al., 2022). These findings support the "cry-for-help" model in which pathogen perception in one plant compartment causes chemical changes belowground that recruit protective partners. Host signaling pathways can participate directly in this recruitment. Treatment of tomato with Bacillus cereus AR156 altered salicylic acid- and jasmonic acid/ethylene-related responses, remodeled root exudates, and enriched multiple bacterial genera negatively associated with *Ralstonia* colonization (Yang et al., 2023a). Host genetics can exert a similarly strong effect. The tomato ripening-inhibitor transcription factor influenced root exudate profiles, the abundance of disease-suppressive *Streptomyces*, and resistance to *R. solanacearum*; application of specific exudate compounds restored microbiome suppressiveness in the mutant background (Yang et al., 2023b). This provides a mechanistic link between plant genes, root chemistry, microbiome assembly, and disease phenotype.

Neighboring plants can also modify this defensive recruitment. In tomato-potatoonion intercropping, root-exudate-mediated interactions enhanced recruitment of Bacillus and generated a microbiome suppressive to *Verticillium dahliae*. Taxifolin released in the intercropping context altered tomato root chemistry and indirectly promoted beneficial colonization (Zhou et al., 2023). These results suggest that crop diversity can function as a form of microbiome engineering. More broadly, studies of suppressive soils indicate that repeated pathogen pressure can select plant-associated microbial communities with enhanced protective functions across plant generations or cropping cycles (Spooren et al., 2024; Liu et al., 2026). The rhizosphere shield is therefore jointly constructed by plant genotype, environmental history, neighboring plants, microbial responses, and pathogen-induced signaling.

4. Disease-Suppressive Soils and Synthetic Microbial Communities

Disease-suppressive soils are natural experiments demonstrating that microbial communities can override otherwise favorable conditions for disease. Suppressiveness may arise from broad community activity or from particular functional guilds and can sometimes be transferred to conducive soil through small amounts of suppressive soil, indicating a biological basis (Spooren et al., 2024; Du et al., 2025). Recent network-based studies show that suppressive rhizospheres frequently contain greater numbers of beneficial or antagonistic taxa and more complex interactions than disease-conducive systems. In Fusarium solani-suppressive soil, bacterial and fungal keystone taxa were identified and subsequently validated as antagonists, demonstrating how community profiling can be converted into causal biological control experiments (Li et al., 2024).

Synthetic microbial communities provide a reductionist route for reproducing this protective function. Instead of relying on one inoculant, SynComs combine strains selected for complementary traits such as antagonism, root colonization, biofilm formation, nutrient competition, immune activation, and cross-feeding. A large tomato study constructed bacterial, fungal, and mixed communities from cultured rhizosphere isolates and found that cross-kingdom SynComs provided the strongest suppression of Fusarium wilt, emphasizing functional complementarity (Zhou et al., 2022). In watermelon, a 16-strain core bacterial community derived from grafted plants improved growth and Fusarium resistance in ungrafted plants, and simplified combinations retained protective effects through synergistic interactions (Qiao et al., 2024). Importantly, community composition can contain predictive information before disease becomes obvious. In tomato, minor early differences in rhizosphere assembly forecast later bacterial wilt outcome, suggesting that disease management could eventually move from symptom-

based intervention toward microbiome-based risk diagnosis (Gu et al., 2022). Similar reasoning underlies current attempts to identify core taxa, keystone species, functional genes, and network properties associated with suppressiveness rather than relying solely on taxonomic abundance (Andargie et al., 2023; Liu et al., 2026).

Rhizosphere protection is also capable of extending aboveground. Barley inoculated with defined rhizosphere SynComs showed reduced powdery mildew development even though the pathogen infects leaves, demonstrating that a belowground community can generate systemic protection without requiring direct antagonism at the infection site (Rigerte et al., 2026). Field evidence remains more limited, but analyses of tomato production systems indicate that bio-organic fertilizers, composts, and other biological products can shift resident microbiomes in directions associated with reduced soil-borne disease pressure (Obiazikwor et al., 2025). Together, suppressive soils and SynCom studies show a progression from observation to design: identify protective community states, isolate the organisms or functions responsible, reconstruct them in controlled consortia, and then test whether the resulting shield remains stable in realistic soil and crop environments.

5. Translating the Rhizosphere Shield into Crop Protection

The practical objective is not simply to describe healthy microbiomes but to steer rhizosphere communities toward stable disease-suppressive states. Several strategies are emerging. The first is direct inoculation with single strains or SynComs. Defined communities can provide complementary functions and greater ecological redundancy than individual biocontrol agents, as demonstrated in tomato, watermelon, and barley pathosystems (Zhou et al., 2022; Qiao et al., 2024; Rigerte et al., 2026). However, introduced organisms must compete with established native communities, survive variable temperature and moisture, colonize the appropriate root zone, and retain activity across plant developmental stages.

A second strategy is host-mediated microbiome engineering. Rather than adding microbes, crops can be selected or bred for root traits and exudate profiles that consistently recruit protective taxa. The RIN study in tomato illustrates that a plant regulatory gene can alter metabolites, Streptomyces recruitment, and bacterial-wilt resistance, while intercropping experiments show that neighboring plants can redirect exudation and beneficial colonization (Yang et al., 2023b; Zhou et al., 2023). Such results create opportunities for “microbiome-assisted breeding” and for prebiotic amendments composed of metabolites that selectively stimulate resident beneficial organisms (Spooren et al., 2024). Agronomic practices offer a third route. Crop rotation, intercropping, composts, organic amendments, reduced disturbance, and diversified plant inputs can modify microbial resource availability and network structure, sometimes increasing suppressiveness (Obiazikwor et al., 2025; Liu et al., 2026). Yet management effects are strongly context-dependent. A microbial treatment effective in sterilized substrate may fail in field soil because indigenous competitors, edaphic chemistry, climate, pesticide history, and local pathogen populations alter establishment and function. Therefore, field translation requires experiments that measure not only disease severity but also inoculant persistence, microbiome succession, functional gene expression, yield, and consistency across sites and seasons (Du et al., 2025). Multi-omics technologies can improve this transition by connecting taxonomy to mechanism. Amplicon sequencing identifies community shifts, metagenomics reveals functional potential, metatranscriptomics identifies active pathways, metabolomics characterizes chemical exchange, and culture collections allow direct reconstruction and testing of candidate consortia (Andargie et al., 2023; Li et al., 2024). Longitudinal sampling is particularly valuable because microbiome states associated with future disease may emerge before pathogen abundance or symptoms become diagnostic (Gu et al., 2022).

The next generation of microbiome-based disease management should therefore prioritize function, ecological stability, and host compatibility rather than maximizing microbial diversity alone. Standardized formulation, shelf-life, biosafety, non-target effects, horizontal gene transfer risk, and regulatory classification must also be addressed before complex living products are widely deployed (Liu et al., 2026). A realistic goal is to integrate microbiome engineering with resistant cultivars, cultural control, diagnostics, and judicious pesticide use. In this framework, the rhizosphere biological shield becomes a manageable component of integrated disease management rather than a stand-alone replacement for all conventional measures (Spooren et al., 2024). Recent synthesis of tomato Fusarium wilt management similarly favors integrating biological control with host resistance and complementary measures rather than relying on a single intervention (Kanwal et al., 2024).

6. Conclusion

The rhizosphere microbiome functions as a dynamic biological shield by combining ecological exclusion, nutrient competition, antimicrobial activity, cross-kingdom cooperation, and activation of plant immunity. Recent studies show that plants actively shape this shield through root exudates and genetic regulation, particularly during pathogen attack, while disease-suppressive soils demonstrate that protective microbial states can emerge at ecosystem scale. Synthetic communities now allow these functions to be reconstructed experimentally and, in some cases, transferred to susceptible plants. The central challenge is moving from controlled demonstrations to predictable field performance. Future microbiome-based protection will depend on identifying causal functions, selecting compatible microbial consortia, exploiting host traits that recruit beneficial organisms, and accounting for soil and environmental context. Integration of longitudinal microbiome profiling, metabolomics, functional omics, and microbiome-assisted breeding should make disease-suppressive rhizospheres increasingly designable. Used alongside conventional integrated disease management, this approach offers a biologically grounded path toward more durable and environmentally compatible crop protection.

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OPTIMIZATION OF IPBS RETROTRANSPOSON MARKERS FOR MOLECULAR CHARACTERIZATION AND GENETIC DIVERSITY ASSESSMENT OF PENICILLIUM EXPANSUM ISOLATES

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Abstract
Penicillium expansum causes apple blue mould and may contaminate fruit with patulin. This study evaluated iPBS retrotransposon primers for preliminary molecular characterization of apple-derived isolates from Sivas, Giresun, Isparta, and Amasya, Türkiye. Following species-targeted PCR with PEF/PER, 29 iPBS primers were screened in eight isolates (P1-P8). The annealing temperatures shown in the gel images were used throughout: 14 primers at 50 °C, four at 51 °C, ten at 52 °C, and one at 53 °C. On visual inspection, iPBS-2402, -2244, and -2381 at 50 °C; -2398 at 51 °C; 2252, 2376, and 2087 at 52 °C; and 2401 at 53 °C were shortlisted because their profiles included several readable bands and apparent differences among isolates. Profiles with a dominant shared band, weak amplification, or extensive smearing were less suitable for unambiguous scoring. The interpretation concerns primer suitability in this eight-isolate pilot, not a completed population-genetic analysis. Neither independent PCR replicates nor a verified presence/absence matrix were supplied; therefore, polymorphism rates, genetic distances, and geographic structure were not calculated. Reproducibility should be confirmed at the gel-image temperatures before the primers are used on the larger isolate collection. The present results define experimentally grounded conditions for that follow-up while keeping species identification, band-based fingerprinting, and quantitative diversity estimation analytically distinct.
Keywords: *Penicillium expansum*; iPBS; retrotransposon; molecular characterization; primer optimization.

Introduction

Penicillium expansum is a principal cause of blue mould in stored pome fruit, and its capacity to produce patulin makes reliable monitoring relevant to both postharvest losses and food safety (Luciano-Rosario el al., 2020). Molecular confirmation of species identity and assessment of variation within a confirmed species address different questions. Previous work documented variation among *P. expansum* strains associated with different hosts, while recent regional studies have emphasized differences in Penicillium sp. composition and patulin production (Sanzani et al., 2013; Dudaš et al., 2025).

Inter-primer binding site amplification targets genomic intervals between primer-binding sites of LTR retrotransposons. Its use does not depend on prior sequence characterization of the study organism (Kalendar et. al., 2010). For diversity analysis, however, the value of a primer depends on distinct and reproducible differences among isolate profiles, rather than on band number or intensity alone. We therefore screened 29 iPBS primers to identify informative candidates and their reported best annealing temperatures for subsequent genetic characterization of *P. expansum* isolates. An iPBS band difference does not, by itself, demonstrate a new retrotransposon insertion or element activity: primer binding and the distance between target sites also affect amplification.

Species identification is a distinct requirement from within-species fingerprinting. In a Serbian survey, Žebeljan et al. (2021) recovered *P. expansum* together with *P. crustosum* and *P. solitum* from stored pome fruit and used multilocus evidence to clarify species boundaries. Shen et al. (2024) similarly examined 62 *Penicillium* strains from diseased apples in China with ITS, BenA, and CaM sequence data and resolved several species associated with blue mould. These findings justify the separation of the

species-targeted PEF/PER assay from the subsequent iPBS diversity screen; variation in an iPBS gel is not by itself evidence of species identity.

Biological variation within *P. expansum* creates a second analytical question. Sanzani et. al. (2013) investigated strains from apple, sweet cherry, and table grape and described variation linked to host of origin. Maldonado et al. (2022) studied 103 isolates from Argentina and Spain through morphological, metabolomic, and β-tubulin approaches; despite similarities in several phenotypic traits, the sequence analysis resolved multiple haplotypes. The latter result illustrates why a marker set should be evaluated for its capacity to distinguish isolates that may otherwise look similar. In the present pilot, however, all documented source material was apple and no provincial mapping of P1-P8 was supplied.

The rationale of iPBS is the presence of primer-binding sites associated with LTR retrotransposons dispersed across eukaryotic genomes. Kalendar et al. (2010) established a method that does not require a target-genome sequence for initial primer development. Özer et al. (2016) applied the approach to multiple fungal taxa and obtained discriminatory fingerprints. Their study supports the feasibility of an iPBS screen in fungi, but its numerical polymorphism results cannot be transferred to this *P. expansum* primer set. Band quality and discriminatory capacity must be measured under the DNA, reaction, annealing, and electrophoresis conditions of the current experiment.

The aim was to compare the amplification profiles of 29 iPBS primers in eight P-coded isolates, identify bands that can be scored consistently, and report the primer-specific annealing temperatures recorded in the gel images. These images represent the selected outcomes of gradient PCR. In the absence of a replicate band matrix, this work establishes a shortlist for validation, rather than a numerical ranking of marker informativeness or an estimate of population structure.

Genome-based evidence shows that isolates assigned to *P. expansum* cannot be assumed to be genetically uniform. Julca et al. (2016) compared seven geographically separated *P. expansum* genomes and described within-species genomic variation and patterns consistent with recombination. Their findings support molecular comparisons among regional isolates, while the modest genome sample limits population-level inference. PCR fingerprints do not provide the resolution of genome sequencing; here, the immediate objective of iPBS screening is to find primers yielding distinguishable, reproducible fragments.

The biological relevance of isolate variation extends beyond distinguishing fingerprints. Samaras et al. (2020) investigated efflux-transporter overexpression in fungicide multidrug-resistant *P. expansum* strains at the transcriptome level; Luciano-Rosario et al. (2023) used functional genetics to investigate candidate loci affecting virulence during apple decay. These studies address questions that require independent experiments. An anonymous iPBS fragment alone cannot establish fungicide resistance, patulin production, or virulence.

Materials and Methods

Isolates and DNA preparation

Single-spore purification was documented for the stock isolates. Variable DNA concentrations or degraded templates can produce inconsistent dominant-marker bands, so DNA concentration and integrity were checked before PCR. P1-P8 showed the eight separate lanes per primer in the screening images. The original stock collection may contain additional isolates; the gel images do not show that all stocks were screened. Dates, cultivar names, storage sites, and the individual province for each P code were unavailable, precluding any attribution of band differences to those factors.

The stock collection consisted of single-spore isolates recovered from apples collected in Sivas, Giresun, Isparta, and Amasya, Türkiye. Eight isolates coded P1-P8 were represented in the supplied iPBS gel images. As no mapping between P codes and provinces was supplied, no geographic grouping was assigned. Genomic DNA was prepared using a modified CTAB procedure; concentration and purity were assessed spectrophotometrically, DNA integrity was checked on 1% agarose, and extracts were adjusted to approximately 40-50 ng/µL.

PCR conditions for isolate species identification

Species-targeted PCR used PEF (5′-ATCGGCTGCGGATTGAAAG-3′) and PER (5′-AGTCACGGGTTTGGAGGGA-3′), with a 404-bp expected amplicon in the supplied protocol. A 10-µL reaction contained 5 µL of 2× Phanta Max Master Mix, 0.5 µL of each primer, 1 µL of DNA, and 3 µL of water. Cycling comprised 95 °C for 3 min; 35 cycles of 95 °C for 15 s, 58 °C for 15 s, and 72 °C

for 15 s; and 72 °C for 5 min. The laboratory notes report positive identification, but a separate species-diagnostic gel was not supplied for independent isolate-level assessment.

PCR conditions for iPBS genetic-diversity screening

Primer sequences were transcribed from the accompanying spreadsheet. Annealing temperatures were transcribed exclusively from the labels embedded in the six gel images. Eight P-coded isolate lanes were compared for each primer. An iPBS reaction used one primer to generate a multilocus fingerprint; the species-targeted PEF/PER assay used a forward and reverse primer pair. The molecular-size ladder aids approximate assessment of fragment mobility, but precise fragment sizes were not assigned from these composite gel images. The qualitative decision rule emphasized clear bands above background, interpretable amplification in several of the eight lanes, and visually distinct presence or absence at corresponding migration levels. Brightness by itself was not treated as a genetic variant, and diffuse smear or faint uncertain signal was not scored as an allele. No numerical band counts, reproducibility estimates, or polymorphism percentages were derived in the absence of replicate gels and an independently checked binary matrix.

The reported 20-µL iPBS reaction comprised 2 µL of PCR buffer, 2 µL of dNTP solution, 5.6 µL of water, 3.2 µL of a single primer, 2 µL of $MgCl_2$ solution, 0.2 µL of Taq polymerase (5 U/µL), and 5 µL of DNA. As the stock/final concentration notation in the laboratory notes is ambiguous, only component volumes are reported here. Cycling comprised 95 °C for 3 min; 30 cycles of 95 °C for 15 s, primer-dependent annealing for 1 min, and 72 °C for 1 min; and 72 °C for 5 min. The general laboratory protocol lists a 50-65 °C annealing range; the selected gradient-PCR gel images record primer-specific working temperatures of 50, 51, 52, and 53 °C. Products were resolved in 2% agarose with 1× TBE at 115 V for 2 h 40 min using a 100-3000-bp ladder. Gel interpretation was qualitative.

Findings and Discussion

The gel images show 14 primers at 50 °C, four at 51 °C, ten at 52 °C, and one at 53 °C. These temperatures, embedded in the images as outcomes of gradient PCR, were used for every primer in both tables. iPBS-2402, 2244, and 2381 (50 °C), 2398 (51 °C), 2252, 2376, and 2087 (52 °C), and 2401 (53 °C) offered the most promising visually interpretable fingerprints (Table 1, 2; Figures 1-6). This selection rests on readable, potentially differentiating bands in the P1-P8 lanes. It is provisional because repeatability and information content have not been quantified.

Table 1. Sequences of all 29 screened primers and annealing temperatures transcribed from the six gel images

Primer	Sequence (5′-3′)	Gel-image T_a
iPBS-2074	GCTCTGATACCA	50 °C
iPBS-2382	TGTTGGCTTCCA	50 °C
iPBS-2384	GTAATGGGTCCA	50 °C
iPBS-2245	GAGGTGGCTCTTATACCA	50 °C
iPBS-2246	ACTAGGCTCTGTATACCA	50 °C
iPBS-2402	TCTAAGCTCTTGATACCA	50 °C
iPBS-2381	GTCCATCTTCCA	50 °C
iPBS-2385	CCATTGGGTCCA	50 °C
iPBS-2386	CTGATCAACCCA	50 °C
iPBS-2278	GCTCATGATACCA	50 °C
iPBS-2244	GGAAGGCTCTGATTACCA	50 °C
iPBS-2257	CTCTCAATGAAAGCACCA	50 °C
iPBS-2380	CAACCTGATCCA	50 °C
iPBS-2255	GCGTGTGCTCTCATACCA	50 °C
iPBS-2218	CTCCAGCTCCGATTACCA	51 °C
iPBS-2249	AACCGACCTCTGATACCA	51 °C
iPBS-2398	GAACCCTTGCCGATACCA	51 °C
iPBS-2400	CCCCTCCTTCTAGCGCCA	51 °C
iPBS-2252	TCATGGCTCATGATACCA	52 °C
iPBS-2399	AAACTGGCAACGGCGCCA	52 °C

Primer	Sequence (5′-3′)	Gel-image T_a
iPBS-2375	TCGCATCAACCA	52 °C
iPBS-2376	TAGATGGCACCA	52 °C
iPBS-2391	ATCTGTCAGCCA	52 °C
iPBS-2087	GCAATGGAACCA	52 °C
iPBS-2387	GCGCAATACCCA	52 °C
iPBS-2392	TAGATGGTGCCA	52 °C
iPBS-2229	CGACCTGTTCTGATACCA	52 °C
iPBS-2231	ACTTGGATGCTGATACCA	52 °C
iPBS-2401	AGTTAAGCTTTGATACCA	53 °C

Table 2. iPBS primers shortlisted by visual inspection and their gel-image annealing temperatures.

Primer	Sequence (5′-3′)	Gel-image T_a	Qualitative reading
iPBS-2402	TCTAAGCTCTTGATACCA	50 °C	Multiband candidate
iPBS-2244	GGAAGGCTCTGATTACCA	50 °C	Multiband candidate
iPBS-2381	GTCCATCTTCCA	50 °C	Multiband candidate
iPBS-2398	GAACCCTTGCCGATACCA	51 °C	Distinct levels
iPBS-2252	TCATGGCTCATGATACCA	52 °C	Multiband candidate
iPBS-2376	TAGATGGCACCA	52 °C	Multiband candidate
iPBS-2087	GCAATGGAACCA	52 °C	Common bands; rescore
iPBS-2401	AGTTAAGCTTTGATACCA	53 °C	Multiband candidate

Predominantly shared strong bands in iPBS-2384 and -2257 may offer limited discrimination, whereas iPBS-2380 and -2255 amplified weakly. In iPBS-2246, 2399, and 2387, intense or smeared regions complicate reliable band calls. iPBS-2087 shows sharp products, yet its apparently shared bands make quantitative discrimination uncertain until scored. Consequently, this pilot does not establish a polymorphism percentage or demonstrate a geographic population structure. Replicate amplifications, matched DNA input, negative controls, and independent binary scoring are prerequisites for such analyses. This interpretation is consistent with the need to distinguish the measurement of within-species variation from the prior species-diagnostic PCR (Sanzani el al., 2013).

The gel images reveal substantial differences in primer performance. At 50 °C, iPBS-2074 produced some apparent lane differences, but uneven amplification weakened its priority. A strong common product dominated iPBS-2384, which could conceal weaker discriminating fragments; products from iPBS-2245 and 2382 were often faint. In contrast, iPBS-2402 produced a more consistently interpretable multilocus profile, and iPBS-2244 and -2381 showed several visible levels suitable for follow-up. These observations motivate retesting rather than a claim that any primer already has a measured information content. At 51 °C, iPBS-2398 yielded several discernible fragment levels. iPBS-2249 also amplified, although diffuse fluorescence in some lanes complicates binary scoring; iPBS-2400 produced fewer confidently distinctive levels. The separate 52 °C gel image shows iPBS-2252 and 2376 with several potentially scorable products. The same image also contains iPBS-2391, 2399, and 2375. Their temperatures in this study are all 52 °C, as printed on that image; no annealing temperatures were assigned from the primer spreadsheet. The later gel images include readable products for iPBS-2087 at 52 °C and iPBS-2401 at 53 °C. The relatively strong shared fragments of iPBS-2087 may ultimately reduce its discriminatory value even if amplification proves reproducible. Some iPBS-2401 lanes differ in intensity, but intensity is not equivalent to band presence or absence. iPBS-2387 and -2399 show regions of saturation or extensive smearing and were not chosen for immediate scoring. Matched template input, exposure, gel conditions, and a second PCR run are necessary to distinguish technical signal variation from reproducible polymorphism.

Özer et al. (2016) found that iPBS markers can differentiate fungal isolates across several taxa. Their conclusions provide a methodological comparator, although their reported polymorphism estimates arise from a different species set and systematically scored bands. Maldonado et. al. (2022) compared Argentine and Spanish *P. expansum* isolates using β-tubulin haplotypes. Our proposed dominant-marker

screen neither reproduces their sequence-based test nor estimates comparable diversity indices; it identifies primers worth applying to a larger sample. In both comparisons, an assay's suitability must be assessed in the context of its sampling and scoring design. The multilocus species analyses of Žebeljan et al. (2021) and Shen et al. (2024) further support separating species confirmation from subsequent within-species variation. A positive PEF/PER note is useful, but the diagnostic gel and sequence confirmations were not part of the provided figure set. Dudaš et al. (2025) compared *Penicillium* species in relation to patulin production; no toxin assay, virulence test, or fungicide phenotype was performed in the present marker screen. Accordingly, the observed iPBS bands cannot be interpreted as evidence of patulin production or pathogen aggressiveness.

For a future quantitative study, ambiguous fragments should be excluded. A band should enter the 1/0 matrix only if it reappears at the same migration position in independent PCRs and can be scored without knowing isolate identity. Only then can Jaccard similarities, ordination, and clustering be estimated. Tests of provincial differentiation also require a sample design and metadata matching each isolate to its collection site. The expression "best primers" in this paper refers solely to a qualitative shortlist from the available gel images, not to a ranked numerical polymorphism index. Temperatures refer to the values printed on the corresponding gel images.

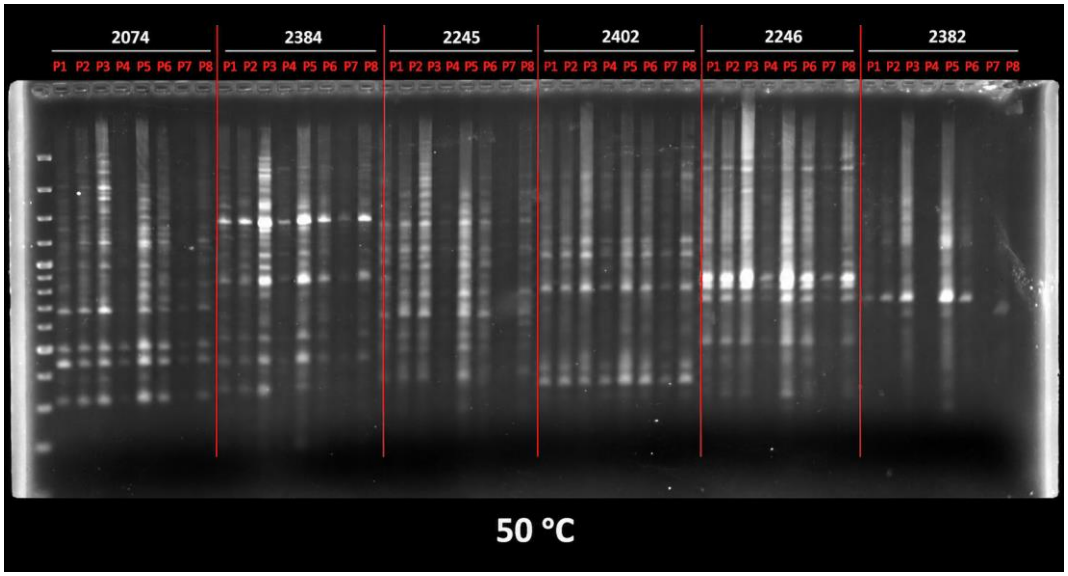


Figure 1. Gel image at 50 °C across eight P-coded isolates; iPBS-2402 is a priority candidate.

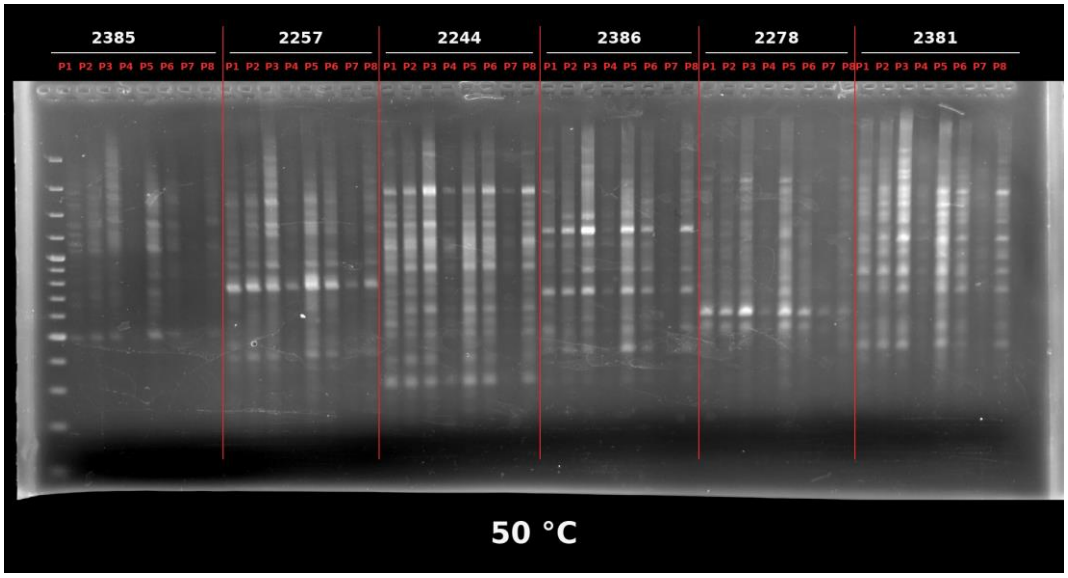


Figure 2. Gel image at 50 °C; iPBS-2244 and -2381 are shortlisted for confirmation.

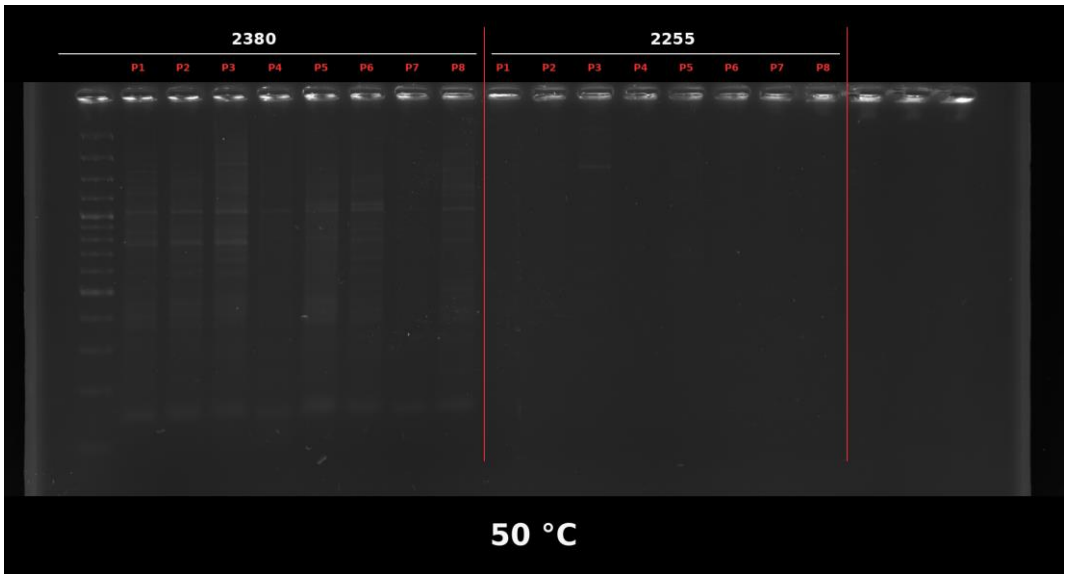


Figure 3. Gel image at 50 °C showing weak amplification with iPBS-2380 and -2255.

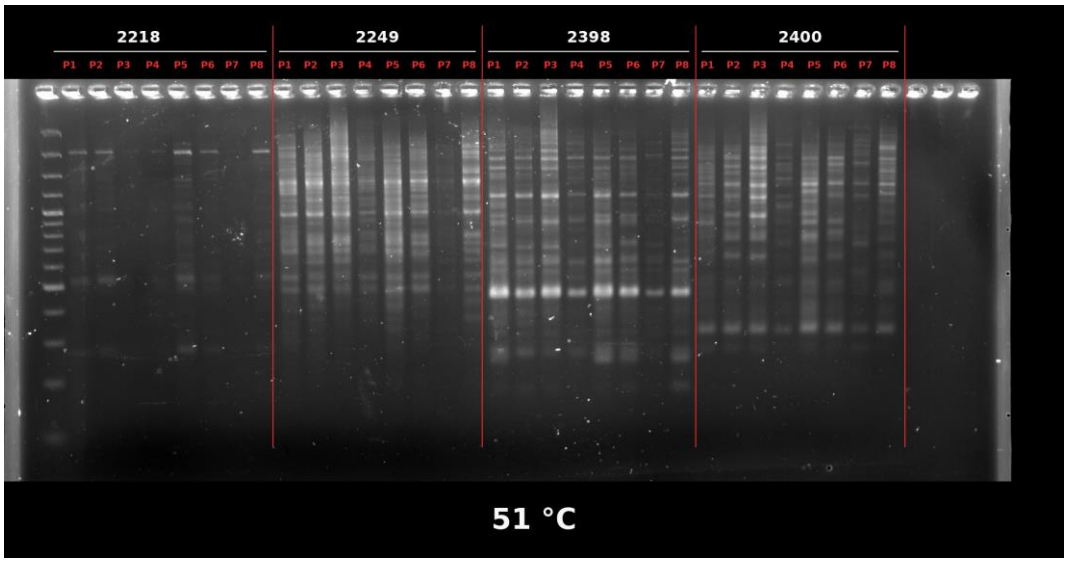


Figure 4. Gel image at 51 °C including iPBS-2398; diffuse products of other primers need confirmation.

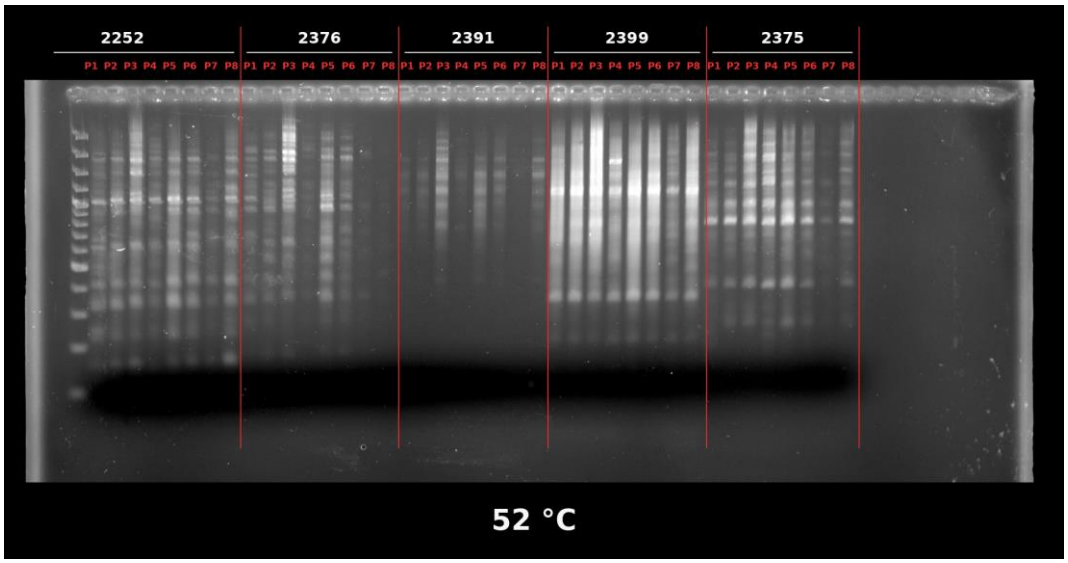


Figure 5. Gel image at 52 °C showing iPBS-2252 and -2376 among the screened primers.

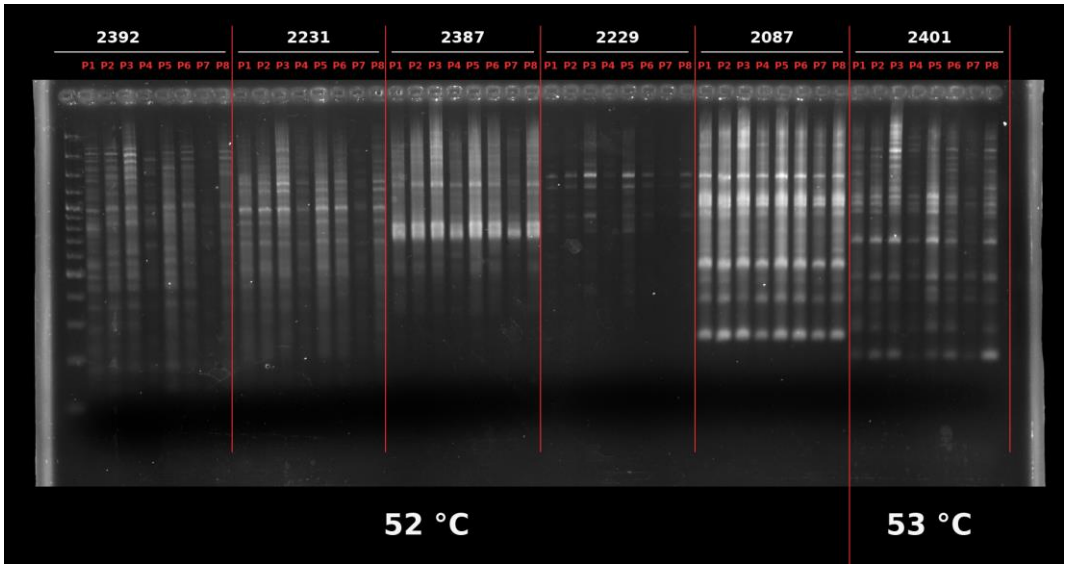


Figure 6. Gel image showing iPBS-2087 at 52 °C and iPBS-2401 at 53 °C.

Evidence from other microorganisms helps place the iPBS screen in a methodological context. Aydın et al. (2022) applied iPBS to 96 Saccharomyces cerevisiae isolates sampled across four Turkish regions to examine genetic diversity and population structure. Primer performance in yeast cannot be transferred directly to Penicillium, because the distribution of amplifiable sites and band quality depend on the organism and PCR conditions. Accordingly, the ranking derived from gel images of eight isolates is a preliminary selection for P. expansum, rather than a measured discriminatory-power estimate supported by replicate genotyping.

The genomic variation documented by Julca et al. (2016) supports extending this study to a larger isolate collection if the selected fragments prove reproducibly polymorphic. Samaras et al. (2020) and Luciano-Rosario et al. (2023), however, addressed fungicide response and virulence through distinct functional approaches. The present iPBS bands have not been validated as diagnostic markers for these traits. A future assessment of possible associations with patulin concentration, fungicide sensitivity, or fruit pathogenicity would require independent phenotype measurements, more isolates, and appropriate statistical validation.

Conclusion and Recommendations

The qualitative assessment of 29 iPBS primers in eight P-coded isolates shortlisted iPBS-2402, -2244, -2381, -2398, -2252, -2376, -2087, and -2401. The selected annealing temperatures shown in the gel images were 50, 51, 52, and 53 °C, depending on the primer. Specifically, 2252 and 2376 belong to the 52 °C gel image. Distinct bands are candidate markers only after they prove reproducible in independent amplifications. A validated presence/absence matrix and a broader, traceable isolate sample are prerequisites for diversity indices and comparisons among collection sites. First, each P1-P8 code should be linked to its stock number, province, collection date, apple cultivar, and any recorded storage environment. The species-diagnostic gel image, negative control, and ideally confirmatory multilocus sequence records should be linked to the same identifiers. Traceable sample identities will make it possible to distinguish biological differences from specimen mislabelling or mixed cultures. Documentation of single-spore purification is essential when a later banding pattern is assigned to one isolate. Second, the shortlisted primers should be reamplified at the temperatures printed in their gel images: 50 °C for 2402, 2244, and 2381; 51 °C for 2398; 52 °C for 2252, 2376, and 2087; and 53 °C for 2401. At least two independently prepared PCRs with matched DNA input are needed to establish reproducibility. Stock and final concentrations of primer, buffer, nucleotides, $MgCl_2$, and template must be confirmed from laboratory records before a transferable protocol is published. Diffuse or saturated products warrant systematic optimization of template input and reaction specificity. Third, the final primer set should be evaluated through blind binary scoring by two readers of bands that are sharp and replicated. Any disagreement should be resolved by repeating the gel, after which total and polymorphic

band counts and isolate similarities can be calculated. A larger collection balanced across provinces and collection contexts would then support explicit tests of geographic structure. Phenotypes such as toxin output or virulence could be evaluated separately if measured. This sequence of work turns the current optimization pilot into a defensible genetic-diversity study without assigning unsupported statistics to the preliminary gels.

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IDENTIFICATION OF INFORMATIVE SCOT MARKERS FOR GENETIC DIVERSITY ANALYSIS OF PENICILLIUM EXPANSUM ISOLATES

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Abstract
Penicillium expansum is a major cause of blue mould in stored apples and is associated with patulin contamination. This study screened start codon targeted (SCoT) primers as candidates for future genetic diversity analysis of apple-derived *P. expansum* isolates. Single-spore stock cultures from Sivas, Giresun, Isparta, and Amasya were subjected to species-targeted PEF/PER PCR, while the available SCoT gel images show four coded isolates (P1-P4). Eighteen primer labels occur across two gel images; the accompanying sequence spreadsheet contains 18 primer entries, but lists SCoT-25 where the image identifies SCoT-26. Consequently, 17 imaged labels can be matched unambiguously to supplied sequences; the SCoT-26 sequence requires confirmation and SCoT-25 cannot be scored from these images. The documented SCoT protocol used annealing at 50 °C. Visual assessment prioritised SCoT-3, -5, -19, and -22 for repeatability testing; SCoT-1 and -2 are secondary candidates. Intense common bands, faint lanes, and background signal lowered confidence in several other primers. These observations identify candidates, not measured polymorphism rates or population structure. Independent PCRs, explicit band scoring, resolution of the primer-label discrepancy, and a larger provenance-balanced isolate set are required before diversity parameters can be reported.
Keywords: *Penicillium expansum*; SCoT; apple blue mould; primer screening; genetic diversity; agarose gel.

Introduction

Postharvest blue mould of apple is closely associated with *Penicillium expansum*. The pathogen can colonise wounded fruit during handling and cold storage, and its ability to produce patulin makes isolate monitoring relevant to food safety as well as product loss (Luciano-Rosario et al., 2020). Yet a blue mould lesion does not establish species identity: several *Penicillium* species may coexist in stored fruit. Species confirmation and comparisons within a confirmed species are therefore separate analytical steps. Recent surveys of apples and other pome fruit recovered multiple *Penicillium* species and showed that pathogenicity and toxin production should be evaluated independently (Žebeljan et al., 2021; Shen et al., 2024; Dudaš et al., 2025). Understanding variation among *P. expansum* isolates is relevant when designing collections for epidemiological studies and selecting strains for subsequent functional work. Sanzani et al. (2013) investigated variation related to host of origin, whereas Maldonado et al. (2022) combined morphological, β-tubulin, and metabolomic observations on isolates from Argentina and Spain. A comparison of genome sequences also demonstrated measurable intraspecific variation in geographically distributed *P. expansum* isolates (Julca et al., 2016). Results from these studies cannot be assigned to the present isolates without matched phenotypic or sequence data; instead, they justify first establishing a reproducible marker set.

Start codon targeted polymorphism is a single-primer amplification method developed from a short conserved region around the ATG translation initiation codon in plant genes (Collard & Mackill, 2009). Because the target concept concerns gene-associated sequence motifs, SCoT primers are often described as gene-targeted; a product's genomic position or function, however, must be established by sequencing before it can be called a functional marker in a particular fungus. The original assay yielded predominantly dominant profiles, so presence and absence of reproducible amplicons, rather than band

intensity alone, form the basis of fingerprint analysis (Collard & Mackill, 2009). The adaptation of SCoT to fungi is supported by independent examples, but primer performance is not portable across taxa. Aydın et al. (2022) investigated yeast isolates from Turkish sourdough, and Gajera et al. (2016) studied mycoparasitic *Trichoderma koningii* using SCoT-derived variation. Palacıoğlu et al. (2023) assessed multiple plant-pathogenic fungal species with SCoT markers, and Özer et al. (2026) examined Fusarium from wheat. Together these studies show that fungal SCoT amplification is feasible while also making clear that a fungal primer screen requires species-specific and experiment-specific assessment. Molecular marker studies distinguish technical amplification, reproducibility, and biological informativeness. A bright product shared by all isolates confirms amplification but may carry little discriminatory information. Conversely, an apparent absence in a faint lane could reflect low DNA input, amplification failure, or variation at a priming site. Oliveira and Azevedo (2022) reviewed the diversity of fungal marker systems and their distinct analytical uses. For the present four-isolate screen, the immediate questions are which labelled primer groups yield discrete, interpretable fragments and which issues in the supplied records must be resolved before quantitative analysis.

Our objective was to examine the two supplied SCoT gel images, link their labels to the supplied sequence list, and prioritise primers for a reproducible *P. expansum* fingerprinting workflow. We retain the species-specific identification assay and the reported SCoT PCR conditions as separate methodological stages. We deliberately restrict conclusions to the observed four-lane gel profiles: no repeat amplification records, scored binary matrix, phenotypes, or isolate-to-province mapping were supplied. Thus the work is an evidence-based primer selection and documentation study rather than a completed population-genetic analysis.

Materials and Methods

Isolates and DNA preparation

The source protocol describes pure, single-spore isolates recovered from apples collected in Sivas, Giresun, Isparta, and Amasya, Türkiye. Cultures were maintained in the stock collection at -80 °C and +4 °C. The two provided SCoT gel images label four isolate lanes per primer (P1-P4), and no province-by-code map is available; statements about geographic grouping or allele frequencies therefore cannot be made. Mycelial material was collected by centrifugation of suspensions in sterile water or by scraping from culture plates. Genomic DNA was isolated using a modified CTAB-based procedure, checked by spectrophotometry and a 1% agarose gel, and stored at -80 °C. The source notes 40-50 ng/µL for prepared stocks; the amount stated for each subsequent PCR is reported separately because the dilution between these stages is not specified.

PCR conditions for isolate species identification

The species-directed reaction used PEF (5′-ATCGGCTGCGGATTGAAAG-3′) and PER (5′-AGTCACGGGTTTGGAGGGA-3′), for an expected 404-bp product as described in the supplied PCR record and linked there to Sanzani et al. (2013). A 10-µL reaction comprised 5 µL 2× Phanta Max Master Mix (Vazyme P525), 0.5 µL of each forward and reverse primer (listed as 10 pM in the source), 3 µL nuclease-free water, and 1 µL template DNA (50 ng/µL in the source table). Cycling was 95 °C for 3 min; 35 cycles of 95 °C for 15 s, 58 °C for 15 s, and 72 °C for 15 s; followed by 72 °C for 5 min. The source describes positive species-directed results in stock isolates; the supplied SCoT photographs themselves do not contain a separately labelled PEF/PER gel, so their bands are not used to reconfirm species identity.

PCR conditions for SCoT genetic diversity screening

The recorded 20-µL single-primer amplification mixture contained 2 µL PCR buffer, 2 µL dNTP solution, 5.6 µL distilled water, 3.2 µL primer, 2 µL $MgCl_2$ solution, 0.2 µL Taq DNA polymerase (5 U/µL; 1 U/reaction), and 5 µL genomic DNA (25 ng stated in the protocol). The supplied record describes buffer as 1×, dNTPs as 2 mM, primer as 5 mM, and $MgCl_2$ as 2 mM without consistently distinguishing stock concentrations from final concentrations; these labels are transcribed as recorded and require laboratory-sheet verification before replication. The program states 95 °C for 5 min and 35 cycles including 95 °C for 1 min and 50 °C annealing for 1 min, followed by 72 °C for 8 min. The duration of a within-cycle 72 °C extension is absent from the record and is not invented here. The 50 °C value comes from the SCoT protocol: unlike the earlier iPBS material, neither SCoT gel image prints a primer-specific gradient temperature.

Gel electrophoresis and source reconciliation

Products were resolved on 2% agarose in 1× TBE at 115 V for 2 h 40 min. A GeneRuler 100-3000 bp marker (Thermo Scientific, SM0333) is specified in the PCR record. Slide images were reviewed at their original pixel resolution, retaining the original image labels rather than redrawing bands. Primer sequences were transcribed from the supplied spreadsheet; the gel names SCoT-26, which the sequence sheet omits, while the sheet lists SCoT-25, which does not appear on either gel. This discrepancy was treated as unresolved rather than silently mapping the sequence of SCoT-25 to SCoT-26.

Primer evaluation and limits of scoring

Primers were assessed qualitatively for visible amplification in P1-P4, discrete bands, between-lane differences potentially suitable for scoring, background smearing, signal saturation, and missing or very faint lanes. Bands were not converted into a binary matrix because independent PCR repeats, exposure calibration, and lane-to-isolate metadata were unavailable. No polymorphic-band percentage, resolving power, polymorphic information content, similarity coefficient, dendrogram, AMOVA, or inferred population structure was calculated. The shortlist identifies candidates for validation, not empirically ranked genetic-diversity estimates.

Findings and Discussion

The two source gel images together display 18 primer labels: SCoT-1, -2, -3, -5, -6, -8, -9, -11, -12, -13, -14, -16, -19, -21, -22, -23, -24, and -26. Each region is annotated with P1-P4, but the formatting of SCoT-12 and -16 places one P4 annotation away from its primer heading; precise lane alignment in that area should be confirmed against the original gel notebook. The image sequence corresponds to Table 1, except for the SCoT-25/SCoT-26 mismatch. Matching only by apparent band pattern cannot fix a primer-identity error. On the first gel image, SCoT-3 produces several discernible bands across P1-P4, with apparent differences in the lower-to-mid migration region. SCoT-5 also yields relatively readable bands in all four lanes, although the strongest products are shared. These two primers are primary candidates because multiple clear features can be revisited in independent reactions. SCoT-1 gives a multilocus profile, with additional lower bands of variable apparent visibility; its lane background and faint features warrant a conservative secondary priority. SCoT-2 contains a pronounced lower shared band and some higher fragments that might help distinguish lanes, but dominant common signal limits the confidence of a single-image assessment.

SCoT-6 has little convincing amplification in the supplied image and cannot support diversity scoring in its present form. SCoT-8 shows marked lane-to-lane imbalance, including weak or absent signal in a central lane, which cannot be interpreted as a genotype-specific null band without repeat amplification. SCoT-9 produces bright, partly saturated products and diffuse background. Strong common products and high signal are prominent in SCoT-11 and -14; SCoT-12 has limited clearly separable features in the shown lanes. SCoT-13 is relatively faint, while SCoT-16 includes strong shared bands but uncertainty in the final lane annotation. These primers are not assigned quantitative informativeness from the photographs alone. On the second gel image, SCoT-19 provides several resolved bands across four lanes and visible differences in band occurrence or strength at more than one migration level. Because the last lane appears weaker for some products, this is a promising primer whose candidate polymorphisms need strict technical replication. SCoT-22 shows multiple products, including lower bands suitable for checking across P1-P4; despite some uneven background, it is another primary candidate. SCoT-21 is dominated by a common band, whereas SCoT-23 has a strong lower product and less clear information above it. SCoT-24 has multiple products but conspicuous lane streaking and strong common fragments, making it a conditional reserve primer.

The final gel group bears the label SCoT-26 and contains visible amplification in P1-P4, but its sequence is absent from the supplied list. No sequence is provided for a reliably identifiable SCoT-26 primer; any recommendation to order or reproduce it would risk using the unrelated SCoT-25 sequence. Conversely, SCoT-25 has a listed sequence but no corresponding image-based performance result. The mismatch affects one of 18 imaged names and one of 18 listed sequences; the other 17 name-to-sequence pairs are directly reconcilable.

Based on readable fragment distributions rather than a numerical polymorphism score, SCoT-3, -5, -19, and -22 constitute the principal shortlist. SCoT-1 and -2 may be retained as secondary candidates if repeat experiments confirm their weaker or more ambiguous features. This order is intentionally provisional: a primer with numerous shared bands may prove less informative than one with fewer but

repeatable differences, and a visually missing band may become a strong product when template input is standardised. Table 2 records the evidence and conditions that each candidate must meet before inclusion in a final fingerprinting set.

Table 1. Primer labels, supplied sequences and the source reconciliation.

Primer	Sequence (5′-3′)	Source status
SCoT-1	CAACAATGGCTACCACCA	Image + sheet
SCoT-2	CAACAATGGCTACCACCC	Image + sheet
SCoT-3	CAACAATGGCTACCACCG	Image + sheet
SCoT-5	CAACAATGGCTACCACGA	Image + sheet
SCoT-6	CAACAATGGCTACCACGC	Image + sheet
SCoT-8	CAACAATGGCTACCACGT	Image + sheet
SCoT-9	CAACAATGGCTACCAGCA	Image + sheet
SCoT-11	AAGCAATGGCTACCACCA	Image + sheet
SCoT-12	ACGACATGGCGACCAACG	Image + sheet
SCoT-13	ACGACATGGCGACCATCG	Image + sheet
SCoT-14	ACGACATGGCGACCACGC	Image + sheet
SCoT-16	ACCATGGCTACCACCGAC	Image + sheet
SCoT-19	ACCATGGCTACCACCGGC	Image + sheet
SCoT-21	ACGACATGGCGACCCACA	Image + sheet
SCoT-22	AACCATGGCTACCACCAC	Image + sheet
SCoT-23	CACCATGGCTACCACCAG	Image + sheet
SCoT-24	CACCATGGCTACCACCAT	Image + sheet
SCoT-26	—	Image only; sequence unverified
SCoT-25	ACCATGGCTACCACCGGG	Sequence only; no gel image

Note: SCoT-25 has no gel image and SCoT-26 has no verified sequence; neither was substituted for the other.

Table 2. Qualitative candidate primers and the next verification step.

Primer	Priority / visual observation	Validation
SCoT-3	Primary; resolved bands	Repeat lower-middle bands
SCoT-5	Primary; multiband	Verify weaker bands
SCoT-19	Primary; band differences	Check P4 signal
SCoT-22	Primary; several products	Resolve low bands
SCoT-1	Secondary; faint lower bands	Confirm repeatability
SCoT-2	Secondary; common intense band	Score only discrete bands

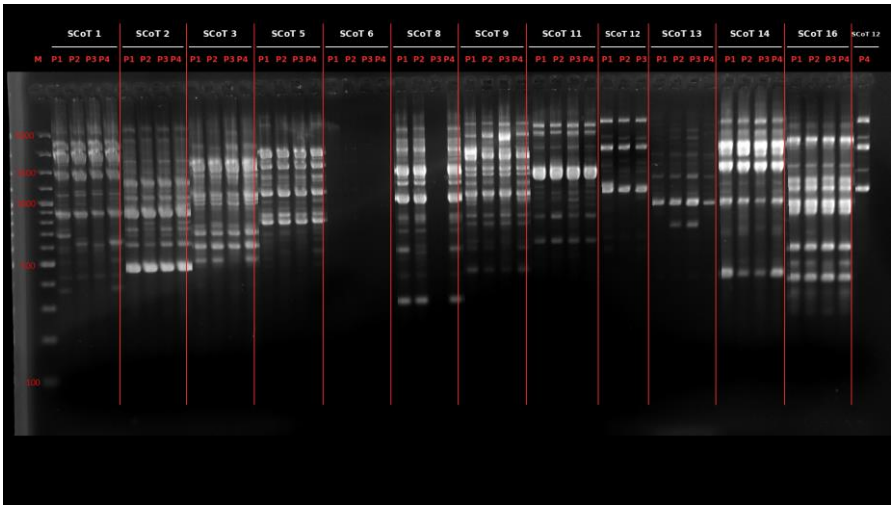


Figure 1. First original SCoT gel image showing the labelled primer groups SCoT-1 through -16 and P1-P4 lanes. Red separators and labels are already part of the supplied image; apparent intensity differences are not scored as quantitative polymorphism.

The labelled regions in this original image are useful for tracing a provisional assessment back to a specific primer and lane. Nevertheless, neighbouring regions share one gel background and differ in signal strength. Interpretation should therefore focus on clearly separated fragments within a primer group, while accounting for uneven lane loading and the possibility that bright common products conceal weaker bands. In particular, the near absence of signal with SCoT-6 and imbalance among SCoT-8 lanes are technical prompts for repeat amplification, not evidence that P-coded isolates lack a corresponding genetic locus.

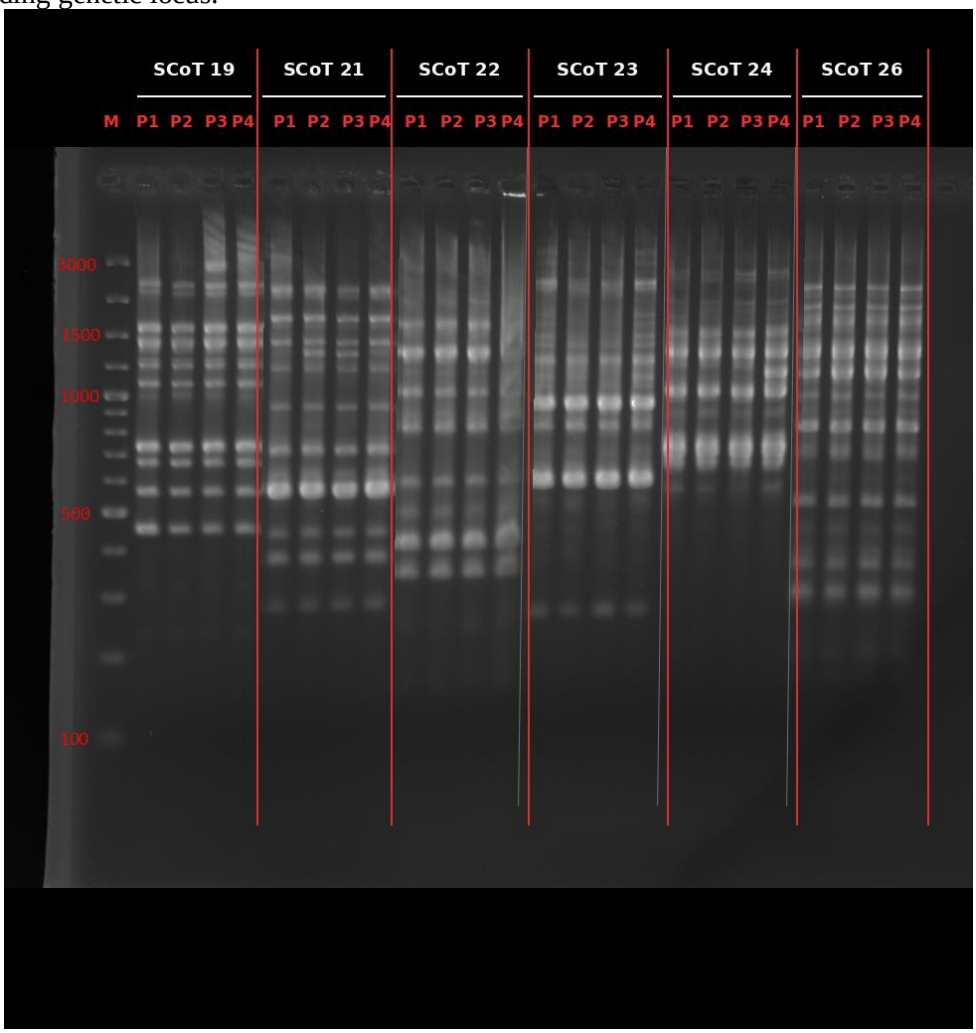


Figure 2. Second original SCoT gel image showing SCoT-19, -21, -22, -23, -24 and photographed SCoT-26. The SCoT-26 primer sequence is not present in the supplied spreadsheet.

An informative primer is not simply the primer producing the most bands. Intense fragments shared by every lane may serve as controls for successful amplification while providing little discrimination. A putative isolate-specific fragment may be more useful, but only if it recurs in separately prepared PCRs. Selection should be based on the number of repeatable variable loci, the proportion of missing data, and the capacity of the combined primer set to distinguish isolates. Without these measures, SCoT-3/-5/-19/-22 is an experimentally motivated candidate set rather than a validated optimal combination. The SCoT name does not establish a functional effect for an anonymous amplified fragment. The original SCoT method relied on single 18-mer primers and 50 °C annealing and explicitly tested reproducibility with independently conducted PCRs (Collard & Mackill, 2009). The current DNA record also specifies 50 °C, but our gels contain neither a printed gradient comparison nor independent technical runs. It would therefore be inaccurate to call 50 °C an experimentally optimised, primer-specific annealing temperature in this dataset. It is the documented working condition for this screen and a starting point for a future small gradient around the recorded setting if nonspecific smears persist.

Several fungal studies offer useful methodological comparisons. Aydın et al. (2022) used SCoT markers in yeast from Turkish sourdough, and Palacıoğlu et al. (2023) evaluated 96 isolates spanning ten fungal species with a larger primer screen before calculating population-level summaries. Gajera et al. (2016) analysed SCoT variation in *T. koningii*, whereas Güney et al. (2023) applied SCoT in Alternaria associated with lemon black rot. Özer et al. (2026) extended the approach to wheat-associated Fusarium. These studies establish biological feasibility in fungal systems; none supplies an estimate of how many polymorphic *P. expansum* loci the present four lanes contain, and transferring published polymorphism percentages here would be misleading.

The first analytical boundary is taxonomic. SCoT primer fragments generated from a mixed *Penicillium* collection could reflect species differences rather than intraspecific variation. Multiple blue-mould-associated *Penicillium* sp. were recovered in published surveys (Žebeljan et al., 2021; Shen et al., 2024; Dudaš et al., 2025). The source record reports PEF/PER-positive *P. expansum* stocks, but the SCoT gels alone are not species-confirmatory evidence. Before comparative analysis, isolate codes should be linked to the diagnostic PCR record and, where feasible, a sequence-confirmed reference for taxonomically ambiguous cultures. The second boundary is biological interpretation. Sanzani et al. (2013) and Maldonado et al. (2022) assessed diversity in *P. expansum* using designs that addressed host or geographic context, while Julca et al. (2016) compared genomes and detected appreciable within-species variation. The four P-coded lanes here have no verified provenance-by-lane key, replication, or scored matrix. Neither a geographic cluster nor a genetic distance can be inferred from visual differences in these images. The bands are candidate dominant loci; two equal-migrating fragments also need not be homologous without sequence confirmation.

A third boundary concerns phenotypic inference. Samaras et al. (2020) investigated multidrug resistance through transcriptomic analysis; Luciano-Rosario et al. (2023) used functional genetics to study virulence in apple. Neither fungicide response, patulin production, nor infection severity was measured for P1-P4 in the supplied record. Even where an eventual SCoT locus lies near a coding region, a band difference alone cannot establish a causal gene or predict any of these phenotypes. Trait association requires isolate-level phenotyping, adequate sample size, and independent validation. The primer identity inconsistency is experimentally consequential. SCoT-25 and -26 are distinct catalogue identifiers; substituting the spreadsheet entry for the photographed name would undermine the reproducibility of any future paper. The PCR record also leaves the within-cycle extension unspecified and labels some reaction constituents ambiguously. Resolution should come from laboratory worksheets, tube labels or purchase records, and original thermocycler programs. Correcting these source fields is part of quality control rather than an opportunity to infer missing values from typical published conditions.

Band-scoring practice determines whether the selected primers ultimately become informative. Replicate products should be imaged under a consistent exposure; clearly separated fragments at the same migration position can then be called present or absent with a documented tolerance. Ambiguous or saturated features should be coded missing, not force-scored. Across a larger balanced isolate collection, one could report total and polymorphic fragments per primer, the proportion of reproducible polymorphic bands, resolving power and binary similarity as applicable. Oliveira and Azevedo (2022) provide context for choosing complementary fungal marker approaches when independent confirmation is needed.

Conclusion and Recommendations

Validation can proceed in three stages. First, repeat P1-P4 with the four primary and two secondary primers in two independently prepared reactions, retaining only reproducible bands. Second, expand the successful set to additional separately collected single-spore isolates whose species identity and sample provenance have been confirmed. Third, compare SCoT and iPBS profiles on the same DNA samples while scorers remain unaware of geographic origin. The chosen primers should be reassessed at each stage: a primer that amplifies cleanly can still fail to reveal reproducible variation in a larger collection. The supplied two SCoT gel images support a carefully bounded primer-screening result. Eighteen primer names were photographed in four isolate lanes per name, and 17 photographed names match sequences in the provided workbook. SCoT-3, -5, -19, and -22 show the most promising combination of visible multi-band amplification and potentially scorable between-lane differences; SCoT-1 and -2 merit secondary testing. The 50 °C annealing condition originates from the SCoT PCR protocol, not a

temperature gradient printed on these images. These recommendations represent a practical shortlist and cannot be interpreted as a numerical ranking of polymorphism or diversity. The first priority is to reconcile the photographed SCoT-26 with the workbook's SCoT-25. A dated primer inventory, oligonucleotide order confirmation, original tube label, and experiment log should establish which primer was amplified. The SCoT-26 profile must remain excluded from a sequence-identified recommended set until this is resolved. Likewise, SCoT-25 should be described as listed but untested in the supplied gel images. The unusual concentration labels in the SCoT mixture and the missing within-cycle extension duration also require verification from the experimental record before the protocol is reproduced or submitted as fully specified. The second priority is to link P1-P4 unambiguously with specimen identifiers, collection province, cultivar, isolation date, and species-confirmation evidence. The positive PEF/PER record should be connected to each actual gel lane; representative ambiguous isolates should receive an independent sequence-based taxonomic check. DNA quality and input should be normalised across samples. At least two independently prepared PCRs on separate days should then be performed for each shortlisted primer, followed by electrophoresis and imaging under matched conditions. A faint, saturated, or discordant band should never be converted into a polymorphic locus on the basis of one image. Only after a repeatable set is established should blinded readers generate a documented 0/1 presence-absence matrix, agreeing on a band size window, minimum intensity threshold and missing-data rule before viewing sample origins. Primer-level total and polymorphic band counts and a transparent measure of resolving capacity may then be calculated. Inferences about geographic structure require a substantially larger collection with balanced sampling by region and appropriate statistical analysis; four lanes cannot support reliable province-specific diversity estimates. If association with patulin, virulence, or fungicide sensitivity is desired, these traits must be measured separately in the same individually identified isolates.

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YAPAY ZEKA DESTEKLİ YÜKSEK VERİMLİ FENOTİPLEME İLE YEM BİTKİLERİ ISLAHI

ARTIFICIAL INTELLIGENCE AND HIGH-THROUGHPUT PHENOTYPING IN FORAGE CROP BREEDING

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ÖZET
Yem bitkileri, hayvansal üretimin sürdürülebilirliği, yüksek kaliteli kaba yemin güvenilir bir şekilde temini ve tarımsal ekosistemlerin korunması açısından önemli bir rol oynamaktadır. Bununla birlikte, geleneksel yöntemler kullanılarak yonca, fiğ, korunga, üçgül ve çeşitli yemlik buğdaygil türlerinde biyokütle verimi, yem besin değeri, çevresel stres toleransı ve biçim sonrası yeniden büyüme kapasitesi gibi karmaşık fenotipik özelliklerin kapsamlı bir şekilde değerlendirilmesi önemli bir fenotipleme engeli oluşturmaktadır. İnsansız hava araçları, farklı kamera sistemleri (RGB, multispektral, hiperspektral, termal), LiDAR ve yer sensörlerini birleştiren yüksek verimli fenotipleme, çok sayıda genotipin hızlı, tahribatsız ve standart biçimde incelenmesine olanak tanır. Ayrıca, yapay zekâ ve ileri makine öğrenimi teknikleri bu teknolojik platformlar tarafından üretilen yüksek boyutlu verilerin etkin biçimde analiz edilmesi, biyokütle ve kalite özelliklerinin tahmin edilmesi, erken stres sinyallerinin hızla tespit edilmesi ve üstün genotiplerin hassas bir şekilde seçilmesi için yeni olanaklar sunmaktadır. Bu çalışma, temel sensör teknolojilerini, veri işleme tekniklerini, yem bitkisi çeşitlerindeki tarla uygulamalarını ve arazi kısıtlamalarını dikkate alarak, yapay zekâ destekli yüksek verimli fenotiplemenin günümüz yem bitkileri ıslahındaki rolünü kapsamlı bir şekilde değerlendirmektedir. Nitekim fenotipik, genomik ve çevresel parametrelerin entegre edilmesi, seçim hassasiyetini artırarak iklim koşullarına adaptasyonu yüksek kaliteli çeşitlerin ıslah sürecini belirgin şekilde kısaltmaktadır.
Anahtar kelimeler: Yapay zeka, İklim değişikliğine dayanıklılık, Yem bitkileri ıslahı, Yüksek verimli fenotipleme

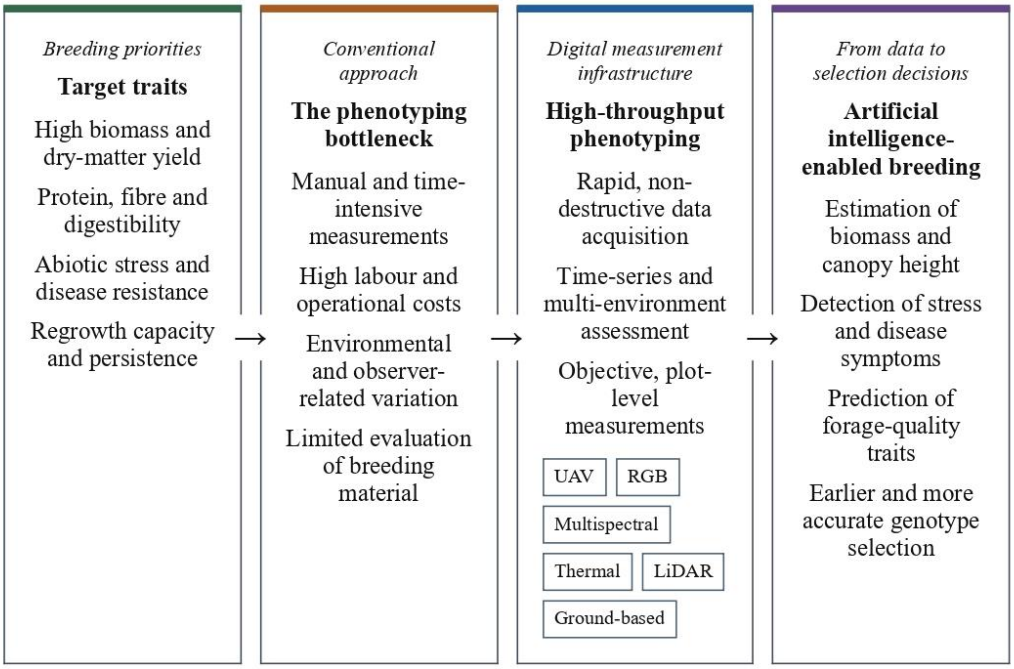
ABSTRACT
Forage crops play an essential role in the sustainability of animal agriculture, the reliable supply of high-quality forage, and the enduring health of agricultural ecosystems. Nevertheless, thoroughly evaluating complex phenotypic traits such as biomass yield, forage nutritional value, environmental stress tolerance, and post-harvest regrowth capacity in species such as alfalfa, vetch, sainfoin, clover, and assorted forage grasses using conventional methods remains a major phenotyping challenge. High-throughput phenotyping enables rapid, non-invasive, and highly uniform assessment of numerous genotypes by systematically integrating uncrewed aerial vehicles, sophisticated RGB, multispectral, hyperspectral, and thermal imaging systems, LiDAR technology, and terrestrial sensors. Moreover, artificial intelligence and advanced machine learning techniques offer new opportunities to efficiently analyse the vast, high-dimensional data generated by these platforms, predict biomass and quality traits, rapidly detect early stress signals, and precisely select superior genotypes. This study comprehensively evaluates the role of artificial intelligence-augmented high-throughput phenotyping in contemporary forage crop breeding, considering key sensor technologies, data processing techniques, field applications in forage varieties, and notable operational limitations. In conclusion, integrating phenotypic, genomic, and environmental data can greatly improve selection accuracy, accelerating the development and market introduction of climate-resilient, high-quality forage crops.
Keywords: Artificial intelligence, Climate resilience, Forage crop breeding, High-throughput phenotyping.

INTRODUCTION

Forage crops are an essential resource for satisfying the energy, protein, and structural carbohydrate demands of ruminants, thereby supporting the economic sustainability of livestock production (Li and Brummer, 2012). Plants such as alfalfa, vetch, sainfoin, and clover are notable for their exceptional roughage yield, attributed to their increased protein concentration (Annicchiarico, 2015). These species can reduce the demand for mineral nitrogen fertilisers by supplying biological nitrogen inputs through symbiotic nitrogen fixation (Peoples et al., 2009). In addition, the root systems of perennial forage plants provide substantial advantages in soil organic carbon, aggregate stability, and erosion resistance (Lemaire et al., 2014).

In forage crop cultivation, the primary goals of dry matter and biomass output influence total roughage generation (Li and Brummer, 2012). At the same time, feed nutritional quality and resulting animal performance are governed by crude protein, neutral detergent fibre, acid detergent fibre, lignin, and digestibility (Jung and Allen, 1995). The main variables hindering yield and sustainability in forage crops are drought, heat, cold stress, as well as diseases and pests (Annicchiarico, 2015). When selecting better genotypes in perennial species, it is essential to concurrently evaluate post-harvest regrowth, winter hardiness, and long-term persistence (Annicchiarico, 2015; Li and Brummer, 2012).

Figure 1. Conceptual framework of artificial intelligence-assisted high-throughput phenotyping in forage crop breeding



Evaluating these attributes using standard methodologies requires extensive labour, time, and financial resources in experiments with many plots and genotypes (Furbank and Tester, 2011). Visual scoring is vulnerable to observer bias, which can lead to subjective errors in assessing sickness or stress (Cobb et al., 2013). Furthermore, because growth phases and environmental variables strongly affect plant phenotypes, a single evaluation point may not capture variability in genotype performance (Araus and Cairns, 2014). Thus, phenotyping is identified as a primary hindrance in current plant breeding practices (Furbank and Tester, 2011). Figure 1 illustrates the conceptual transition from target breeding traits and conventional bottlenecks to artificial intelligence-assisted high-throughput phenotyping.

HIGH THROUGHPUT PHENOTYPING AND SENSOR TECHNOLOGIES

The Scope of High-Throughput Phenotyping

High-throughput phenotyping (HTP) refers to the rapid, non-invasive, and consistent evaluation of numerous plants or plots using imaging, automation, and sensor technologies (Yang et al., 2020). A primary benefit is that it allows repeated assessment of the same genotypes at different developmental

stages. As a result, researchers can examine both ultimate yield and dynamic characteristics, including growth rate, stress response, and post-harvest regeneration (Tardieu et al., 2017). HTP aims to improve the efficiency and accuracy of selection by producing objective, high-resolution phenotypic data, especially in extensive breeding populations (Furbank and Tester, 2011; Yang et al., 2020).

Platforms, Sensors, and Measurable Traits

Phenotyping platforms are generally classified into terrestrial and airborne systems. Unmanned aerial vehicles (UAVs) offer higher spatial resolution and extensive temporal coverage across vast field experiments, enabling rapid observation of entire canopy dynamics (Xie and Yang, 2020). In contrast, terrestrial phenotyping systems operate closer to the canopy, providing detailed structural and physiological information with less atmospheric disruption (Jin et al., 2020). Table 1 summarises the primary sensing platforms, the key traits they evaluate, and their prospective applications in forage crop breeding.

Table 1. Application areas of key platforms and sensors used in high-throughput phenotyping for forage crop breeding

Technology	**Measurable Traits**	**Potential Applications in Forage Crops**
RGB Camera	Canopy cover, colour, area, height-derived structural traits (Volpato et al., 2021)	Biomass and vegetation estimation (Herzig, 2021; Wang et al., 2024)
Multispectral	NDVI, NDRE, GNDVI, chlorophyll-related vegetation indices (Hassan et al., 2019; Fu et al., 2020)	Stress and growth monitoring (Hassan et al., 2019)
Hyperspectral	Spectral signatures, pigments, nitrogen, biochemical traits (Ge et al., 2019)	Estimation of forage quality parameters (Ge et al., 2019)
Thermal Camera	Leaf and canopy temperature (Ji et al., 2026; Deery et al., 2016)	Drought and water stress identification (Araus and Cairns, 2014; Deery et al., 2016)
LiDAR	Plant height, canopy volume, 3D structural architecture (Xie and Yang, 2020)	Biomass and morphological analysis (Xie and Yang, 2020)
UAV / Drone	Rapid, frequent, high resolution spatial data over large areas (Xie and Yang, 2020; Duan et al., 2017)	Genotype comparison in field trials (Araus and Cairns, 2014; Ge et al., 2019)
Ground-Based Sensors	Fine-scale physiological and structural data at proximity (White et al., 2012)	Detailed plot-level evaluation (White et al., 2012; Deery et al., 2016)

RGB imagery can assess plant height by analysing canopy cover, colour, texture, and three-dimensional surface models (Volpato et al., 2021). Multispectral sensors support assessment of plant vitality, chlorophyll condition, and growth-related characteristics through indices such as NDVI and NDRE (Hassan et al., 2019). Thermal imaging provides essential information on plant hydration and stress responses by assessing canopy temperatures (Araus and Cairns, 2014). LiDAR is utilized to quantitatively assess plant height, canopy volume, and three-dimensional structure (Xie and Yang, 2020). Combining structural and spectral data from multiple sensor types markedly improves dry matter yield estimates compared with relying on individual sensor sources (Pranga et al., 2021).

THE ROLE OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Analysis of Large Phenotypic Data

HTP platforms produce substantial data from RGB, multispectral, hyperspectral, thermal, and LiDAR technologies (Xie and Yang, 2020; Yang et al., 2020). Image processing and machine learning techniques enable automatic retrieval of phenotypic variables, including vegetation cover, canopy volume, colour and texture characteristics, vegetation indices, and plant height, from these unprocessed images (Singh et al., 2016). This automation reduces dependence on manual measurements, facilitating assessment of more genotypes over the same trial duration (Furbank and Tester, 2011).

Field data may be affected by variables including varying light conditions, shade, wind, soil background, flight elevation, and sensor calibration (Xie and Yang, 2020). As a result, implement image segmentation, radiometric correction, outlier identification, data filtration, and standardisation procedures before data analysis (Yang et al., 2020). Appropriate calibration methods and experimental frameworks significantly influence the ability to compare data gathered from different time intervals or settings (Araus and Cairns, 2014).

Core Artificial Intelligence Methods

Regression techniques forecast continuous variables such as biomass, dry matter production, plant height, and other quality characteristics. These models often use spectral indices, RGB-based vegetation metrics, and canopy height as inputs (Wang et al., 2024). In alfalfa breeding experiments, UAV-derived RGB and multispectral imagery have been shown to assess plant height and aboveground biomass effectively (Wang et al., 2024).

Tree-based methods like Random Forest and XGBoost deliver strong predictive performance in phenotyping datasets marked by many variables and nonlinear associations (Singh et al., 2016). In addition to their prediction abilities, these models assist in determining which factors, such as pixel counts, vegetation indices, and texture metrics, are most significant for the desired characteristics. A study on Megathyrsus maximus reported predicted accuracies above $r > 0.80$ for both green and dry matter yield using digital characteristics derived from RGB photographs alongside machine learning models (Niederauer et al., 2026).

Support Vector Machines are utilized for classification tasks in high-dimensional datasets (Singh et al., 2016). These methods enable classification of genotypes into healthy and stressed categories or assessment of stress intensity. Convolutional Neural Networks, adept at autonomously discerning colour, shape, and texture patterns from images, show strong efficacy in identifying disease symptoms, classifying weeds, and evaluating developmental stages (Singh et al., 2016). Nonetheless, the reliability of deep learning models depends on adequate labelled training data that reflects a variety of environmental conditions (Yang et al., 2020).

Time series analysis enables examination of growth patterns by repeatedly assessing the same genotypes on several dates (Tardieu et al., 2017). This approach is essential for evaluating characteristics that cannot be measured through isolated timepoint assessments, including growth rate, recovery after stress, post-harvest regrowth, and performance stability across seasons (Yang et al., 2020). For enduring and multiple-harvest forage species, temporal phenotyping enables selection of genotypes based not only on yield capacity but also on reliable performance across multiple developmental phases (Wang et al., 2024).

APPLICATIONS IN FORAGE CROPS

The estimation of biomass and plant height is one of the most advanced application domains of high-throughput phenotyping (HTP) in forage crops. UAV-based structural and spectral data fusion was more accurate than standalone data sources in predicting dry matter yield in perennial ryegrass (Pranga et al., 2021). Different sensors have different advantages for the target traits in alfalfa. For example, multispectral data is helpful for biomass estimation, while RGB data is very good for plant height measurement (Wang et al., 2024).

HTP can also be used for early detection of stress response. Although multispectral indices are valuable in providing information on plant vigor and growth status, thermal imaging can serve as early warning indicators for water stress based on the changes in canopy temperature (Araus and Cairns, 2014; Hassan

et al., 2019). These datasets provide direct field-based phenotypic evidence to support the selection of drought tolerant genotypes.

Hyperspectral data can capture spectral signals of pigments, nitrogen status and some biochemical components, so they are of forage quality (Xie and Yang, 2020). However, the calibration of quality prediction models with laboratory analyzes is rigorous for different species, harvest regimes and environmental conditions. Hence, HTP should be seen as a complementary tool to support the preliminary screening and targeted sampling of large breeding populations rather than as a complete replacement for wet laboratory chemistry.

INCORPORATION WITH GENOMIC SELECTION AND CONSTRAINTS

Secondary characteristics extracted from high-throughput phenotyping could improve the predictive accuracy of complex traits in genomic selection frameworks (Tardieu et al., 2017). Temporal phenotype measurements would allow more detailed analysis of genotype × environment interactions (Yang et al., 2020). This approach sets the stage for data-driven breeding strategies that integrate genomic, phenotypic, and environmental data.

However, HTP applications have several limitations, including high sensor costs, data storage constraints, calibration requirements, experimental design challenges, limited model applicability across contexts, and the need for specialist personnel (Xie and Yang, 2020; Yang et al., 2020). Predictive models should be validated on independent datasets, across different years and conditions, not only on the trials for which they were developed. Successful implementation thus requires the collaboration of plant breeders, remote sensing experts, and statisticians and data analysts.

CONCLUSION

Artificial intelligence-assisted high-throughput phenotyping can facilitate tackling the challenges of manual phenotyping in forage crop breeding. Sensor technologies allow for fast and reproducible monitoring of biomass, plant height, canopy structure, stress responses and specific quality-related traits. These multidimensional datasets are converted through machine learning methods into usable selection decisions, enabling the earlier and more objective identification of superior genotypes. However, rigorous model calibration and multi-environmental validation are still needed for reliable deployment of these technologies. Integration of high-throughput phenotyping, genomic selection and environmental data layers in a seamless manner will accelerate the development of high-yielding, high-quality and climate-resilient forage cultivars in the future.

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REFERANS GENOMLARDAN PANGENOMLARA YEM BİTKİLERİNDE GENETİK ÇEŞİTLİLİK ANALİZİ İÇİN YENİ NESİL YAKLAŞIMLAR

FROM REFERENCE GENOMES TO PANGENOMES NEXT-GENERATION APPROACHES FOR GENETIC DIVERSITY ANALYSIS IN FORAGE CROPS

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ÖZET

Yem bitkileri, ruminant üretiminin temelini oluşturmakla birlikte, bu türlerin ıslahı tür içi genomik varyasyonun yetersiz temsil edilmesi nedeniyle sınırlanmaktadır. Tek bir referans genom, yüksek heterozigotluk, yabancı tozlaşma, poliploitlik ve yoğun tekrarlayan DNA içeriği taşıyan yem bitkisi türlerinde genomik çeşitliliği yeterince yansıtamamaktadır. Bu derleme, genetik çeşitliliğin araştırılması ve genomik bilginin yem bitkileri ıslahına aktarılması açısından doğrusal referans genomlardan pangenomlara geçişi değerlendirmektedir. Uzun okuma dizileme teknolojileri, haplotip çözümlemeli montajlar ve graf tabanlı genom temsilleri, geleneksel kısa okuma eşleştirme yaklaşımlarında sıklıkla gözden kaçan yapısal varyasyonların, kopya sayısı varyasyonlarının ve gen varlığı-yokluğu varyasyonlarının belirlenmesine olanak sağlamaktadır. Yonca, kırmızı üçgül, ak üçgül ve ilişkili buğdaygil sistemlerinden elde edilen bulgular, bu varyasyonların stres adaptasyonu, hastalık yanıtı ve agronomik performans açısından biyolojik önemini ortaya koymaktadır. Çalışmada, temsil gücü yüksek aksessiyonların seçimi, de novo montaj, fazlama, anotasyon, graf oluşturma ve varyant genotiplemeyi kapsayan yem bitkisi pangenomlarının oluşturulmasına yönelik uygulamalı iş akışları ele alınmaktadır. Ayrıca pangenom çapında ilişkilendirme çalışmaları, genomik seleksiyon ve pangenom destekli çekirdek koleksiyon geliştirme yaklaşımları incelenmektedir. Hesaplama gereksinimleri, iş akışlarının standardizasyonu ve yüksek kaliteli yem bitkisi genom montajlarının sınırlı sayıda olması önemli darboğazlar olmaya devam etse de, pangenomik yaklaşım adaptif alellerin keşfedilmesini ve ıslah programlarında kullanılmasını önemli ölçüde geliştirme potansiyeline sahiptir. Başlıca yem baklagilleri ve buğdaygiller için koordineli referans pangenom girişimleri, iklim koşullarına dayanıklı, verimli ve besin değeri yüksek çeşitlerin geliştirilmesi açısından stratejik önem taşımaktadır.
Anahtar Kelimeler: Yem bitkileri ıslahı, Genetik çeşitlilik, Graf tabanlı genom, Pangenom, Yapısal varyasyon

ABSTRACT

Forage crops underpin ruminant production, yet their improvement is constrained by the incomplete representation of within species genomic variation. A single reference genome is particularly insufficient for forage species because many are highly heterozygous, outcrossing and polyploid, and contain extensive repetitive DNA. This review evaluates the transition from linear reference genomes to pangenomes as a framework for investigating genetic diversity and translating genomic information into forage crop breeding. Long-read sequencing, haplotype-resolved assembly, and graph-based representations now enable recovery of structural variants, copy number variants, and gene presence-absence variation that conventional short-read mapping often misses. Evidence from alfalfa, red clover, white clover and related grass systems illustrates the biological relevance of these variants for stress adaptation, disease response and agronomic performance. We discuss practical workflows for constructing forage pangenomes, including selection of representative accessions, de novo assembly, phasing, annotation, graph construction and variant genotyping. We also examine pangenome-wide association studies, genomic selection and pangenome-informed core collection development. Although computational requirements, pipeline standardisation, and the limited number of high-quality forage assemblies remain important bottlenecks, pangenomics can substantially improve the discovery and deployment of adaptive alleles. Coordinated reference pangenome initiatives for major forage legumes

and grasses will therefore be strategically important for breeding climate resilient, productive and nutritionally valuable cultivars.

Keywords: alfalfa, forage breeding, genetic diversity, graph genome, pangenome, structural variation

INTRODUCTION

Genetic diversity is the basis of crop adaptation and sustained genetic improvement. In forage crops, this diversity must support several breeding objectives simultaneously, including biomass yield, persistence, nutritive value, disease resistance and tolerance to increasingly variable temperature and water regimes. The genomic architecture underlying these traits is difficult to capture in a single sequence assembly. Alfalfa (*Medicago sativa* L.), for example, is an autotetraploid, predominantly outcrossing forage legume in which four homologous chromosomes contribute to each chromosome group. Comparable assembly challenges are documented for autotetraploid alfalfa (Chen et al., 2020). Highly heterozygous red clover requires long-read chromosome-scale assembly (Bickhart et al., 2022). Haplotype resolved white clover resources show the additional complexity created by multiple subgenomes (Santangelo et al., 2023).

The reference genome paradigm has enabled marker discovery, genome wide association studies and genomic prediction. Nevertheless, a linear sequence constructed from one genotype necessarily excludes sequences present only in other genotypes. Reads originating from divergent or absent regions can map poorly, be assigned incorrectly or remain unmapped. This phenomenon is commonly described as reference bias (Coletta et al., 2021). It can reduce the detection of insertions, deletions, copy number variants and gene presence absence variants. Graph based pangenomes provide a way to represent this missing diversity (Wang et al., 2022).

A pangenome represents the collective genomic content of a species or breeding population, not the sequence of a single individual. By combining shared sequences with alternative alleles and access-specific sequences, it provides a more complete description of diversity. The aim of this review is to explain why pangenomic approaches are particularly important for forage crops, to summarize the technologies and computational strategies used in their development, and to discuss their integration into diversity analysis and breeding.

GENOMIC COMPLEXITY OF FORAGE CROPS

Polyploidy and Heterozygosity

Polyploidy is widespread among forage species and has important consequences for genome analysis. Autopolyploids such as cultivated alfalfa contain multiple related homologous chromosomes, whereas allopolyploids such as white clover contain distinguishable ancestral subgenomes. Both systems require accurate separation of homologous or homeologous sequence during assembly. If alternative haplotypes are collapsed into a consensus sequence, genuinely distinct alleles and structural variants can be lost. Chen et al. (2020) addressed this challenge by producing an allele aware chromosome level assembly for cultivated autotetraploid alfalfa, demonstrating the feasibility and value of resolving 32 allelic chromosomes. However, a single high-quality assembly does not represent the species as a whole.

High heterozygosity further increases assembly difficulty. Outcrossing forage species maintain diverse haplotypes that are valuable for adaptation but difficult to resolve with short reads. In red clover, a chromosome-scale assembly substantially improved contiguity relative to older fragmented resources and illustrated the importance of long-read sequencing for highly heterozygous allogamous crops (Bickhart et al., 2022). Haplotype resolved white clover resources likewise allow both allelic and subgenomic diversity to be examined more explicitly (Santangelo et al., 2023).

Repetitive DNA and Structural Variation

Transposable elements, consecutive repeats, and duplicated gene families add a second layer of complexity. Short reads often cannot cover repeats, leading to fragmented contigs and ambiguous placement of duplicated sequences. Long-read sequencing supports more complete plant genome assemblies by scanning repetitive intervals (Michael and VanBuren, 2020). Polyploid genomes still require significant coverage and careful phasing (Pucker et al., 2022). Structural variants, traditionally defined as changes larger than approximately 50 bp, include deletions, insertions, inversions, translocations, and copy number alterations. These variants can alter coding dose, promoter context, and

gene regulation, and their contribution to phenotypic diversity may be underestimated when only SNPs are analyzed.

LIMITATIONS OF SINGLE REFERENCE GENOMES

A linear reference offers one coordinate system and one set of alleles at each locus. This representation is efficient for routine alignment but becomes restrictive when a species contains extensive sequence content diversity. Alternative segments cannot be represented at the same coordinate without either excluding them or treating them as non reference sequence. Consequently, mapping based analyses may favor the genotype from which the reference was assembled and may undercall variants in genetically distant landraces, wild relatives or elite breeding material (Coletta et al., 2021).

The biological cost of this omission is clear in Medicago truncatula, a model forage legume. Comparison of multiple de novo assemblies identified substantial novel sequence and extensive structural differences among accessions. many variable gene families were associated with biotic interactions and stress related functions (Zhou et al., 2017). Although M. truncatula is not cultivated alfalfa, it provides a strong proof of concept for the genus: gene content is not fixed within a species, and a single reference cannot adequately characterize all diversity available to breeding. In white clover, copy number differences at loci involved in cyanogenesis have also been linked to environmental adaptation, illustrating how structural variation can affect ecologically important phenotypes (Kuo et al., 2024).

Single reference mapping also limits population genetic interpretation. Genetic distances and diversity statistics based only on callable SNPs exclude unrepresented sequence, whereas presence absence variation may reveal population structure and adaptive differentiation not visible in a SNP only analysis. This is especially relevant to geographically diverse germplasm collections, where local adaptation may be encoded partly by genomic segments absent from a modern reference cultivar.

THE PANGENOME CONCEPT AND GRAPH REPRESENTATION

Core and Accessory Genomic Components

Pangenomes are often described in terms of core and accessory components. Core genes or sequences occur in all sampled genomes, whereas accessory sequences occur in a subset of accessions. Accessory components may be further classified as shell sequences, present at intermediate frequency, and cloud sequences, which are rare or accession-specific. These categories are analytical descriptions rather than fixed biological classes because their estimated size depends on sampling breadth and annotation quality (Gautreau et al., 2020). Crop pangenome resources also emphasize that category estimates change with the assemblies included in the analysis (Naithani et al., 2023). In crop species, accessory genes are frequently enriched for functions related to environmental response, pathogen interaction and specialized metabolism.

From Linear References to Genome Graphs

A graph-based pangenome represents genomic sequence as nodes connected by edges. Each accession or haplotype is stored as a path through the graph. Shared segments are represented once, while alternative alleles or structural variants are represented as branching paths. This avoids forcing all diversity into one linear sequence and enables reads to align against both reference and non-reference alleles. The variation graph toolkit supports read mapping against alternate genomic paths (Garrison et al., 2018). Minigraph enables the construction of reference pangenome graphs (Li et al., 2020). Graph genome frameworks are increasingly used for plant genomic analysis (Wang et al., 2022).

For forage crops, graph representation is attractive because it can retain multiple allelic paths and accession-specific insertions. The approach does not eliminate the need for high quality assemblies. rather, it makes those assemblies more useful by combining them into a shared, navigable structure. A practical pangenome can therefore serve as a population-aware reference for resequencing, transcriptomics and trait mapping. The conceptual contrast between a single linear reference and a graph based pangenome is illustrated in Figure 1.

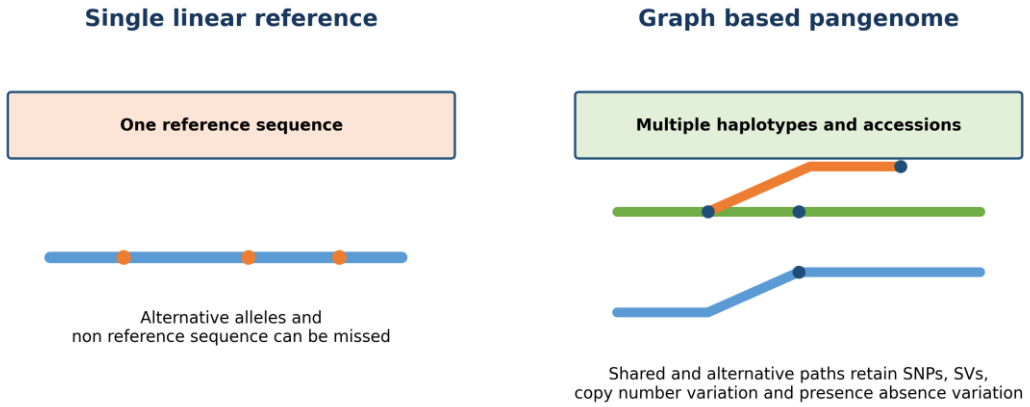


Figure 1. Conceptual comparison of a single linear reference genome and a graph based pangenome.

SEQUENCING TECHNOLOGIES AND PANGENOME CONSTRUCTION

Long Reads and Complementary Data

Short read platforms remain useful for population-scale genotyping because they are accurate and cost-effective. However, they are rarely sufficient on their own to assemble highly repetitive and heterozygous polyploid genomes. PacBio HiFi reads combine long read length with high per-base accuracy, whereas Oxford Nanopore sequencing can generate very long reads that bridge complex repeats and structural variants. Hi-C and optical mapping can provide complementary long-range information for chromosome scaffolding (Michael and VanBuren, 2020). Gametic data can further improve haplotype resolution in autopolyploids (Zhang et al., 2024).

A Practical Forage Pangenome Workflow

Construction begins with purposeful sampling. A founding panel should include elite cultivars, landraces, geographically distinct accessions, material from contrasting environments and, where compatible, wild relatives. The number of assemblies should be sufficient to capture major gene content and structural diversity, but the panel should also remain tractable for high-quality sequencing. Each selected accession is assembled de novo, ideally with haplotype resolution. Assemblies are then assessed for contiguity, completeness, duplicated gene content and correct chromosome assignment before pangenome alignment or graph construction.

The next stages are structural variant discovery, gene annotation harmonization and graph generation. Annotation should use comparable evidence across assemblies to reduce false presence/absence calls caused by unequal gene prediction. The final graph can map short reads from a broader diversity panel, genotype SNPs and structural variants, and estimate the distribution of accessory genes. The major stages and their sequence are summarized in Figure 2. Because no single pipeline is universally optimal, benchmarking with known variants and simulated reads is advisable. Transparent reporting of coverage, phasing quality, graph statistics and callable regions is essential for reproducibility.

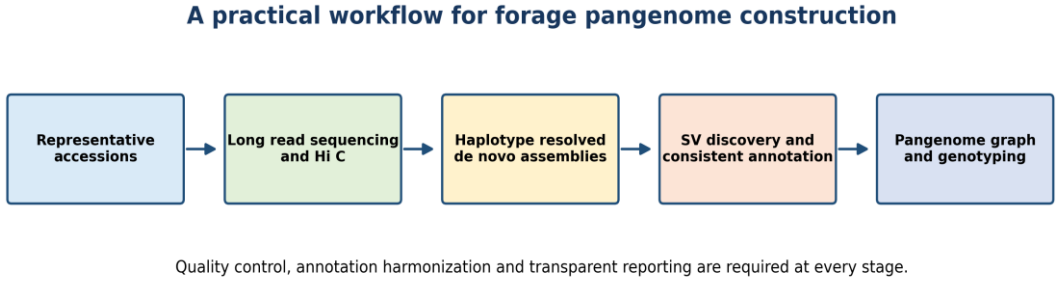


Figure 2. Suggested workflow for constructing a forage crop pangenome.

APPLICATIONS IN GENETIC DIVERSITY AND TRAIT MAPPING

Structural and Functional Diversity

Pangenomes expand diversity analysis beyond SNP frequencies. Presence-absence variants can be encoded as binary markers, copy number variants can be quantified, and complex alleles can be evaluated in their actual haplotypic context. This is particularly valuable for resistance gene clusters and genes associated with secondary metabolism, which often reside in dynamic regions rich in repeats and duplications. A melon graph pangenome increased genotyping density and connected structural variants with fungal resistance (Vaughn et al., 2022).

For forage crops, these approaches can improve the characterization of collections currently described primarily by morphological descriptors or conventional molecular markers. A pangenome-informed diversity panel could distinguish broadly shared genomic backgrounds from rare, potentially adaptive variation in gene content. It can also improve accession selection for a core collection by combining allele frequencies, structural diversity, geographic origin, and phenotypic performance.

Pangenome-wide Association Studies

Conventional GWAS tests SNPs or small indels against phenotypic variation. Pangenome-wide association studies extend the variant set to include structural variants, gene presence/absence states and graph paths. This makes it possible to test whether a gene is present, absent or dosage variable rather than assuming all relevant variation is a nearby SNP in the reference genome. A tomato graph pangenome captured previously missing variation and improved the resolution of breeding relevant associations (Zhou et al., 2022).

The same logic applies to forage traits such as regrowth, winter survival, drought tolerance, digestibility, lignin concentration, and pathogen response. Robust Pan GWAS requires accurate phenotyping across environments, appropriate adjustment for kinship and population structure, and independent validation. Structural variants can be less frequent than SNPs, so rare-variant burden tests, haplotype-based methods, and biologically informed candidate-region analyses may complement single-variant tests.

Climate Resilience and Adaptive Variation

Forage production increasingly depends on varieties that remain productive under drought, heat, cold, salinity and new disease pressures. Local germplasm and wild relatives are important reservoirs of adaptive diversity, but some useful segments may be poorly represented in a cultivar reference. By preserving non-reference sequences, pangenomes can identify candidate genes and genomic regions whose distribution corresponds to environmental gradients or stress-associated phenotypes. They can also clarify whether adaptation involves SNP substitution, gene gain or loss, copy number change, altered gene order or interactions among these mechanisms.

INTEGRATION WITH FORAGE CROP BREEDING

Genomic Selection and Allele Dosage

Genomic selection predicts breeding value from genome wide markers and is particularly useful for complex traits. In polyploid forage crops, prediction accuracy is influenced by allele dosage, linkage disequilibrium, relatedness between training and selection populations, and phenotyping quality. Pangenome-derived markers can enrich prediction models by adding structural and gene content variation to conventional SNP datasets. This does not guarantee improvement in every population. benefit must be evaluated through cross-validation and independent breeding cycles. Genomic selection in forage grasses depends on marker information, phenotyping and relationships between training and selection populations (Resende et al., 2021). Pangenome derived markers may reduce reference bias when they represent causal or tightly linked variation.

Allele aware pangenomes may also help disentangle dosage and haplotype effects in autotetraploid alfalfa. Instead of treating a locus as a simplified biallelic SNP, a graph can retain larger haplotypes and alternate structural forms. Such information could support the selection of favourable haplotype combinations while maintaining genetic diversity needed for long-term improvement.

Germplasm Utilization and Pre-breeding

Gene banks contain a large but incompletely characterized reservoir of forage diversity. Pangenomic information can support pre-breeding by identifying accessions that contribute unique alleles or accessory genes without unnecessarily duplicating already represented genomic content. A pangenome-informed core collection would not simply maximise SNP distance. it would seek to preserve common haplotypes, rare structural variants, adaptive gene content and geographic representation. This strategy could make phenotyping and crossing programs more efficient while retaining the broad diversity required for future climate scenarios. Figure 3 summarizes how pangenomic information can support Pan GWAS, genomic selection and core collection development in forage breeding.

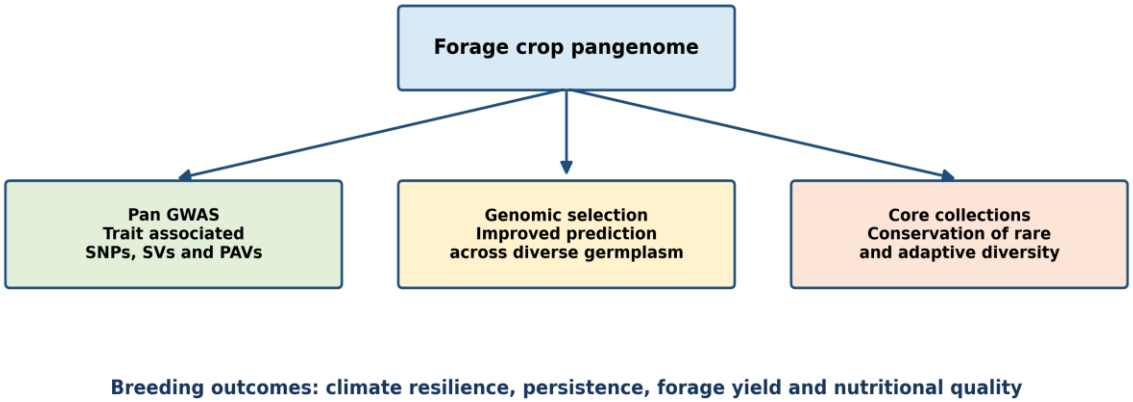


Figure 3. Major pathways through which pangenomic information can support forage crop improvement.

CHALLENGES AND FUTURE PERSPECTIVES

The main constraints are cost, computing infrastructure, and standardization. High-quality de novo compilations and haplotype phasing remain expensive, especially in polyploid species. While graphs generated from numerous compilations can be challenging to store, visualize, and query, pangenome-aware mapping and genotyping require specialized software and careful quality control. In highly heterozygous and polyploid forage plants, the choice of graph representation and sequencing strategy can affect the recovery of structural variation and alternative haplotypes (Kaur et al., 2024; Li et al., 2020). Therefore, standardized data formats, widely accessible workflows, and publicly available repositories are crucial for adoption beyond a small number of well-sourced projects.

A second challenge is sampling design. A pangenome cannot represent all diversity unless the founder genomes capture core breeding pools, ecogeographic groups, and wild or semi-wild material. Inclusion of diverse samples is crucial because a limited or genetically narrow panel may underestimate accessory genome and structural variation within a species (Coletta et al., 2021; Gautreau et al., 2020). Conversely, inclusion of low-quality compilations or inconsistently annotated genomes can lead to artificial variations. Future forage plant pangenomes should be created by international consortia incorporating sequencing, common annotation standards, robust phenotyping, and open data sharing. Coordinated resources for Medicago sativa, Trifolium species, Lolium species, meadow grass, and sainfoin will provide a basis for comparable diversity and breeding studies.

Integration with transcriptomics, epigenomics, metabolomics, and high-throughput phenotyping is the next major opportunity. While a pangenome identifies genomic alternatives, multiple omics data can determine which alternatives are expressed, regulated, or associated with beneficial physiological responses. This integration is particularly important for determining the functional significance of structural variants, copy number variation, and accessory gene content that may contribute to stress adaptation and agricultural performance (Zhou et al., 2017; Kuo et al., 2024). Combining these layers with multiple environmental field trials will enable the transition from descriptive catalogs of variation to validated, viable breeding targets.

CONCLUSION

Pangenomics provides a more realistic representation of forage crop diversity than a single linear reference genome. By recovering structural variants, copy number differences and gene presence-absence variation, it can reveal genomic components that influence adaptation and agronomic performance but are often missed by SNP-centered analyses. Long-read sequencing, haplotype-resolved assembly and graph-based representation are now sufficiently mature to support targeted pangenome initiatives in major forage legumes and grasses. Their greatest value will be realised when pangenomic data are connected to rigorous multi-environment phenotyping, genomic selection and germplasm management decisions. Developing shared reference pangenomes for forage crops is therefore a strategic route toward productive, persistent and climate-resilient cultivars.

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GERMINATION RESPONSES OF ALFALFA CULTIVARS TO SEED COATING, STORAGE AND TRANSFER CONDITIONS

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ABSTRACT
Maintaining high germination performance during post-processing and storage is essential to preserve seed quality and ensure successful stand establishment in alfalfa. This study aimed to determine how seed coating, storage, and transfer processes affect the germination performance of different alfalfa cultivars. Uncoated and coated seeds of five cultivars, Bilensoy, Blue Ace, Bolton, Icon, and Sunter, were evaluated before storage, after storage, and following the transfer process. Germination rate and germination percentage were used as the main indicators of physiological seed performance. The results showed that seed coating, cultivar, and their interactions with storage and transfer stages significantly influenced germination performance. Overall, coating increased the mean germination rate from 83.82% in uncoated seeds to 86.38% in coated seeds. Germination rate remained relatively stable across the evaluation stages, with mean values of 84.88% before storage, 85.20% after storage, and 85.23% after transfer. Bolton (89.21%) and Icon (88.46%) showed the highest overall germination rates, while Sunter had the lowest (80.29%). Coated Icon seeds recorded the highest germination rate (95.50%) after transfer. Similarly, coating increased mean germination from 86.40% to 89.42%, an improvement of about 3.50%. Germination percentage remained stable across storage stages, ranging from 87.60 to 88.08%. Icon (91.38%) and Bolton (90.71%) showed the highest germination percentages, whereas Sunter had the lowest value (83.50%). Coated Icon seeds after transfer showed the highest germination percentage (98.00%). Notably, germination percentage declined from 87.25% to 85.25% in uncoated seeds from pre-storage to post-transfer, whereas it increased from 88.85% to 89.95% in coated seeds. These findings show that seed coating can help maintain and improve alfalfa seed germination during storage and transfer; however, the magnitude of this response is strongly cultivar-dependent. Therefore, genotype-specific optimization of coating and storage protocols may provide an effective strategy for preserving the physiological quality of commercial alfalfa seeds.
Keywords: Germination Percentage, Germination Rate, Seed Coating, Storage, Seed Quality.

INTRODUCTION
Alfalfa (*Medicago sativa* L.) is recognized as one of the most important forage crops worldwide because of its high forage quality, perennial growth habit, broad adaptability, and contribution to agricultural production systems through symbiotic nitrogen fixation (Rocha et al., 2019; Zhang et al., 2022). The establishment of a persistent, uniform, and highly productive stand in alfalfa cultivation largely depends on achieving rapid and uniform germination following sowing. Therefore, commercial seed quality assessment should consider not only final germination percentage but also traits reflecting seed vigor, such as germination speed, emergence speed, and final emergence percentage (Rajjou et al., 2012; Afzal et al., 2020). Germination is a critical developmental stage that begins with water uptake by the dry seed and culminates in the emergence of the embryonic axis through the seed-covering structures, involving interconnected physiological and biochemical processes such as metabolic activation, cellular repair, mobilization of stored reserves, and embryo growth (Rajjou et al., 2012). Consequently, any delay or irregularity during this process may impair uniform stand establishment under field conditions, making the maintenance of germination performance a fundamental quality criterion in alfalfa seed production. One major factor determining germination behavior in alfalfa seeds is physical dormancy, commonly referred to as hardseededness, which is associated with the impermeability of the seed coat to water. Although the embryo remains viable in hard seeds, preventing or delaying water uptake may restrict

germination initiation; therefore, low germination percentages do not necessarily indicate a direct loss of seed viability. Differences in the anatomical and chemical structure of the seed coat have been reported to play a decisive role in water permeability and physical dormancy (Galussi et al., 2015; Li et al., 2025). Moreover, hardseededness may change during storage, and some initially water-impermeable but viable seeds may become permeable over time, thereby increasing the proportion of germinable seeds (Čupić et al., 2005). Conversely, prolonged storage, particularly when temperature, relative humidity, and seed moisture content are not adequately controlled, may accelerate physiological aging, resulting in loss of membrane integrity, increased oxidative damage, and reduced cellular repair capacity (Rajjou and Debeaujon, 2008; Rajjou et al., 2012). Because many of these changes may become evident as reduced germination speed and impaired germination uniformity before a measurable loss of final viability occurs, post-storage seed quality should be evaluated using multiple germination and vigor parameters.

Seed coating technologies are increasingly used to improve the sowing performance and maintain the physiological quality of commercial seeds. Beyond modifying seed physical characteristics, coating treatments can facilitate targeted delivery of nutrients, biostimulants, plant protection products, and beneficial microorganisms directly to the seed microenvironment (Afzal et al., 2020; Paravar et al., 2023). However, the effect of coating on germination may vary depending on the coating material's physical and chemical properties, coating thickness, binder concentration, and, in particular, the coating layer's water and gas permeability. A coating layer with appropriate properties may create a favorable microenvironment around the seed and promote germination, whereas excessive mechanical resistance or low permeability may delay water uptake and coating disintegration, thereby restricting germination speed (Qiu et al., 2020; Sprey et al., 2025). Studies in different species, including alfalfa, have shown that the effects of coating treatments on germination performance may vary by formulation, application rate, environmental conditions, and genotype (Bıçakcı et al., 2018; Arslan et al., 2020; Öten and Tuzlacı, 2024). These findings indicate that the effects of seed coating on germination should not be interpreted as a uniform response but rather within the framework of genotype × coating × environment interactions.

A critical consideration in the commercial use of coated seeds is the extent to which germination performance achieved after coating can be maintained during storage and subsequent transportation/transfer processes. Because coating materials can modify seed moisture balance and water and gas exchange, coated seeds may behave differently during storage than uncoated seeds (Afzal et al., 2020; Sprey et al., 2025). Furthermore, the commercial seed supply chain involves not only storage but also subsequent transfer processes, during which fluctuations in temperature and relative humidity, together with physical stresses, may induce additional changes in seed germination performance. Nevertheless, information regarding the shelf life and post-storage physiological performance of coated seeds remains limited, and interactions among coating, storage, and subsequent handling processes require further investigation (Afzal et al., 2020; Paravar et al., 2023; Rocha et al., 2019). Therefore, evaluating coating, storage, and transfer not as independent factors but as sequential processes to which commercial seeds are exposed before sowing may provide a more comprehensive understanding of the mechanisms that maintain germination performance in alfalfa seeds.

This study comparatively evaluated the germination performance of coated and uncoated seeds from different alfalfa cultivars before storage, after storage, and after storage plus transfer. Specifically, the study aimed to determine the individual and interactive effects of cultivar, seed coating, and storage/transfer processes on germination speed, final germination percentage, emergence speed, and final emergence percentage. By comparing responses of alfalfa cultivars with different dormancy characteristics to coating and storage processes, the study also aimed to determine how well the physiological quality of coated seeds is maintained throughout commercial storage and distribution. The findings are expected to contribute to evaluating seed-coating technologies in alfalfa in terms of germination performance, identifying cultivar-specific responses, and developing management practices to maintain high physiological seed quality during storage and transfer.

MATERIALS AND METHODS

Plant Material

This study was conducted between 2024 and 2025 in the laboratories of the Ankara Seed Registration and Certification Directorate to determine changes in seed physiological quality, germination

performance, and early seedling development of uncoated and coated alfalfa (Medicago sativa L.) seeds before storage, after storage, and after storage plus transportation. Seeds of five alfalfa cultivars representing different dormancy groups, namely Bilensoy-80, Blue Ace, Bolton, Icon, and Sunter, were used as plant material. Seeds from the same seed lot of each cultivar were divided into two groups to compare coated and uncoated seeds. Seed coating was performed by ABEL Tohumculuk A.Ş. at a 1:1 ratio (w/w), corresponding to 1 kg of coating material per 1 kg of seed.

Among the cultivars used in the study, Bilensoy-80 (dormancy group 4) is adapted to the Central Anatolian and Transitional Regions and is resistant to winter conditions, drought, and lodging. Blue Ace (dormancy group 9) is characterized by a semi-erect growth habit, fine stems, a high leaf-to-stem ratio, strong seedling vigor, and adaptation to hot and dry conditions. Bolton (dormancy group 5) is characterized by high fresh and dry forage yields and high crude protein content. Icon (dormancy group 6) is characterized by high seedling vigor and a high leaf-to-stem ratio, as well as resistance to lodging, Fusarium, and Phytophthora. Sunter (dormancy group 5–7) is characterized by a strong and deep root system, rapid regrowth capacity, high forage yield potential, and tolerance to adverse winter conditions. Thus, the study was designed to comparatively evaluate the physiological responses of cultivars differing in genetic and agronomic characteristics and dormancy levels to seed coating, storage, and transportation.

Methods

Germination performance before storage

To determine pre-storage germination performance, seeds were taken from harvested plants that had not yet undergone storage or transportation. Standard germination tests were conducted in accordance with the rules of the International Seed Testing Association (ISTA) to determine the initial physiological quality of the seeds. Germination speed, final germination percentage, emergence speed, final emergence percentage, number of normal seedlings, and number of dead seeds were determined. These values served as baseline data for assessing changes after storage and transportation (ISTA, 2025).

Germination performance after Storage

To determine the effects of storage on seed physiological quality and early seedling development, the seeds were stored for approximately six months at +5 °C and 60% relative humidity. At the end of the storage period, the physiological quality characteristics of the seeds were reassessed in accordance with ISTA rules. Standard germination tests were conducted, and germination speed, final germination percentage, emergence speed, final emergence percentage, number of normal seedlings, and number of dead seeds were determined. The results were compared with the pre-storage values to assess the effects of the six-month storage period on seed physiological quality and early seedling development (ISTA, 2025).

Germination performance before storage after storage + transportation

To determine the effects of transportation following storage on seed performance, seeds stored for approximately six months at +5 °C and 60% relative humidity were subjected to a 16-h transportation period after storage. Following transportation, seed physiological quality was evaluated in accordance with ISTA rules. Standard germination tests were conducted to determine germination speed, final germination percentage, emergence speed, final emergence percentage, number of normal seedlings, and number of dead seeds. The resulting data were compared with the pre-storage and post-storage results to determine the sequential effects of storage and subsequent transportation on seed physiological quality and early seedling development (ISTA, 2025).

Statistical Analysis

The experiment data were analyzed using analysis of variance (ANOVA) in JMP statistical software. For factors and interactions found to be statistically significant by ANOVA, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) multiple comparison test available in JMP (JMP, 2023). Statistical differences were evaluated at the 5% significance level ($p < 0.05$), and differences among means were indicated by letter groupings.

RESULTS AND DISCUSSION

Germination Speed

Analysis of variance showed that coating and cultivar significantly affected germination speed in alfalfa ($p < 0.01$), whereas storage stage had no statistically significant main effect. However, significant coating × storage, cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions ($p < 0.01$) showed that responses to storage and transportation varied considerably by coating status and genotype (Table 1). Based on the overall means, coating increased germination speed from 83.82% in uncoated seeds to 86.38% in coated seeds, corresponding to an increase of approximately 3.05%. Overall means across storage stages were 84.88% before storage, 85.20% after storage, and 85.23% after transportation, indicating that germination speed was largely maintained throughout storage and transportation. Nevertheless, the coating × storage interaction revealed a more distinct response pattern: germination speed in uncoated seeds decreased from 84.05% before storage to 83.10% after transportation, whereas that of coated seeds increased from 85.70% to 87.35% over the same period. These results suggest that seed coating may help maintain germination speed, particularly after storage and transportation.

Table 1. Mean squares from the analysis of variance for germination traits of alfalfa cultivars under different coating treatments and storage stages.

Source of Variation	DF	Germination Speed	Germination Percentage	Emergence Speed
Total	119			
Coating	1	197,633**	273,008**	246,533**
Storage	2	1,525	2,858	119,158**
Coating × Storage Int.	2	21,308**	24,558**	54,758**
Cultivar	4	407,658**	314,988**	902,471**
Cultivar × Coating Int.	4	60,967**	31,571**	73,846**
Cultivar × Storage Int.	8	44,983**	26,150**	95,690**
Cultivar × Coating × Storage Int.	8	35,642**	28,871**	67,352**
Error	90	0,978	1,108	0,867
Source of Variation	**DF**	**Emergence Percentage**	**Number of Normal Seedlings**	**Number of Dead Seeds**
Total	119			
Coating	1	195,075**	19,200**	0,133
Storage	2	163,308**	102,808**	81,325**
Coating × Storage Int.	2	29,025**	13,675**	3,358**
Cultivar	4	892,479**	67,783**	24,229**
Cultivar × Coating Int.	4	84,263**	47,325**	5,363**
Cultivar × Storage Int.	8	91,423**	45,152**	14,523**
Cultivar × Coating × Storage Int.	8	79,056**	46,769**	7,994**
Error	90	0,692	0,750	0,378
Source of Variation	**DF**	**Number of Hard Seed**	**Number of Dead Seeds**	
Total	119			
Coating	1	3,675**	4,408	
Storage	2	1,633**	42,058**	
Coating × Storage Int.	2	0,300	11,908**	
Cultivar	4	8,071**	41,429**	
Cultivar × Coating Int.	4	2,279**	36,971**	
Cultivar × Storage Int.	8	0,540	13,610**	
Cultivar × Coating × Storage Int.	8	1,185**	53,752**	
Error	90	0,303	1,142	

*: $p<0.05$; **: $p<0.01$

Cultivars differed in germination performance. Averaged across coating treatments and storage stages, Bolton (89.21%) and Icon (88.46%) showed the highest germination speeds, followed by Blue Ace (86.33%), Bilensoy (81.21%), and Sunter (80.29%). However, cultivar responses to coating did not follow a consistent pattern. Coating increased germination speed by approximately 6.03% in Bilensoy, 5.14% in Blue Ace, 0.66% in Icon, and 6.76% in Sunter, whereas it decreased germination speed by approximately 2.30% in Bolton. Similar genotypic variation persisted across storage and transportation. After transportation, Icon showed the highest cultivar mean (91.25%), whereas germination speed in Sunter decreased by approximately 4.50% compared with its pre-storage value. The three-way interaction further highlighted this variation, with germination speed across treatment combinations ranging from 75.25 to 95.50%. The highest value (95.50%) was recorded in coated Icon seeds after transportation, whereas the lowest value (75.25%) was observed in uncoated Sunter seeds at the same stage. This difference of about 20 percentage points shows that the effect of coating on germination speed was neither genotype-independent nor unidirectional; instead, it depended on the interaction among coating, genotype, and storage/transportation conditions (Table 2).

Table 2. Mean germination speed (%), germination percentage (%), and emergence speed (%) of alfalfa cultivars under different coating treatments and storage stages, with statistical groupings.

Coating	Storage	Cultivars					Mean
		Bilensoy	Blue Ace	Bolton	Icon	Sunter	
Germination Speed (%)							
Uncoated	Before	76,50^{pq}	84,25^{i-l}	87,75^{efg}	90,75^{bcd}	81,00^{no}	84,05^{c}
	After	81,00^{no}	85,75^{g-k}	91,25^{bc}	86,75^{e-i}	76,75^{pq}	84,30^{c}
	Transportation	79,00^{op}	82,50^{lmn}	91,75^{b}	87,00^{e-h}	75,25^{q}	83,10^{d}
	Mean	78,83^{d}	84,17^{c}	90,25^{a}	88,17^{b}	77,67^{d}	83,82
Coated	Before	83,25^{k-n}	85,75^{g-k}	88,75^{cde}	85,00^{h-l}	85,75^{g-k}	85,70^{b}
	After	86,00^{f-j}	91,25^{bc}	88,50^{def}	85,75^{g-k}	79,00^{op}	86,10^{b}
	Transportation	81,50^{mno}	88,50^{def}	87,25^{e-h}	95,50^{a}	84,00^{j-m}	87,35^{a}
	Mean	83,58^{c}	88,50^{b}	88,17^{b}	88,75^{b}	82,92^{c}	86,38
Mean	Before	79,88^{g}	85,00^{ef}	88,25^{bc}	87,88^{cd}	83,38^{f}	84,88
	After	83,50^{f}	88,50^{bc}	89,88^{ab}	86,25^{de}	77,88^{h}	85,20
	Transportation	80,25^{g}	85,50^{e}	89,50^{bc}	91,25^{a}	79,63^{g}	85,23
	Mean	81,21^{c}	86,33^{b}	89,21^{a}	88,46^{a}	80,29^{d}	85,10
Germination Percentage (%)							
Uncoated	Before	81,00^{l}	88,75^{d-g}	89,00^{c-g}	93,00^{b}	84,50^{l}	87,25^{c}
	After	85,00^{ij}	88,25^{efg}	91,75^{bc}	88,00^{fgh}	80,50^{l}	86,70^{c}
	Transportation	81,50^{kl}	85,25^{hij}	93,00^{b}	87,00^{ghi}	79,50^{ij}	85,25^{d}
	Mean	82,50^{f}	87,42^{d}	91,25^{b}	89,33^{c}	81,50^{f}	86,40
Coated	Before	86,75^{g-j}	88,00^{fgh}	90,25^{b-f}	91,25^{bcd}	88,00^{fgh}	88,85^{b}
	After	88,00^{fgh}	93,00^{b}	91,25^{bcd}	91,00^{b-e}	84,00^{jk}	89,45^{ab}
	Transportation	85,25^{hij}	93,00^{b}	89,00^{c-g}	98,00^{a}	84,50^{ij}	89,95^{a}
	Mean	86,67^{de}	91,33^{b}	90,17^{bc}	93,42^{a}	85,50^{e}	89,42
Mean	Before	83,88^{g}	88,38^{e}	89,63^{cde}	92,13^{ab}	86,25^{f}	88,05
	After	86,50^{f}	90,63^{bcd}	91,50^{ab}	89,50^{cde}	82,25^{gh}	88,08
	Transportation	83,38^{gh}	89,13^{de}	91,00^{abc}	92,50^{a}	82,00^{h}	87,60
	Mean	84,58^{c}	89,38^{b}	90,71^{a}	91,38^{a}	83,50^{d}	87,91
Emergence Speed (%)							
Uncoated	Before	81,00^{ij}	87,75^{ef}	82,75^{hi}	85,00^{gh}	81,00^{ij}	83,50^{c}
	After	78,00^{kl}	93,00^{b}	81,75^{i}	96,50^{a}	68,50^{n}	83,55^{c}
	Transportation	77,00^{l}	87,00^{fg}	87,75^{ef}	90,75^{bcd}	68,50^{n}	82,20^{d}
	Mean	78,67^{f}	89,25^{bc}	84,08^{d}	90,75^{a}	72,67^{g}	83,08
Coated	Before	88,25^{def}	90,25^{cde}	93,25^{b}	93,00^{b}	80,50^{ijk}	89,05^{a}
	After	82,00^{i}	91,00^{bc}	84,75^{gh}	90,00^{cde}	79,00^{jkl}	85,35^{b}
	Transportation	73,00^{m}	84,75^{gh}	90,75^{bcd}	88,25^{def}	80,50^{ijk}	83,45^{c}

	Mean	81,08^{e}	88,67^{c}	89,58^{abc}	90,42^{ab}	80,00^{e}	85,95
Mean	Before	84,63^{cd}	89,00^{b}	88,00^{b}	89,00^{b}	80,75^{e}	86,28^{a}
	After	80,00^{e}	92,00^{a}	83,25^{d}	93,25^{a}	73,75^{f}	84,45^{b}
	Transportation	75,00^{f}	85,88^{c}	89,25^{b}	89,50^{b}	74,50^{f}	82,83^{c}
	Mean	79,88^{d}	88,96^{b}	86,83^{c}	90,58^{a}	76,33^{e}	84,52

[1]Means followed by the same letter are not significantly different.

The higher germination speed observed in coated seeds generally aligns with previous studies showing that appropriate coating treatments can improve seed microenvironmental conditions and promote water uptake and early metabolic activation. Amirkhani et al. (2016, 2019) and Qiu et al. (2020) reported that appropriate biostimulant- and plant protein-based coatings could improve germination speed and uniformity, although the amount and formulation of the coating material determined the direction and magnitude of the response. Similarly, studies in alfalfa by Mehrabi et al. (2015), Bıçakcı et al. (2018), Süheri et al. (2019), and Öten and Tuzlacı (2024) showed that coating effects on germination performance may vary with environmental conditions and application characteristics. The significant cultivar × coating × storage interaction observed in the present study further supports this interpretation. In particular, coated Icon seeds reached the highest germination speed (95.50%) after transportation, whereas uncoated Sunter seeds fell to 75.25%, showing that the physiological advantage of coating was genotype-dependent. This genotypic variation is also consistent with findings from Jungers et al. (2016), Jabri et al. (2021), Xie et al. (2023), and Zhou et al. (2024), who reported that germination and responses to environmental stresses in alfalfa may vary by genetic background. Therefore, these findings show that high and stable germination speed in alfalfa depends not only on coating treatment but also on cultivar × coating × storage/transportation compatibility, highlighting the importance of cultivar-specific optimization of coating technologies in commercial seed production.

Germination Percentage

Analysis of variance revealed that germination percentage in alfalfa was significantly affected by coating and cultivar ($p < 0.01$), whereas the main effect of storage stage was not statistically significant. However, all coating × storage, cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions were significant ($p < 0.01$), indicating that storage and transportation effects varied by coating status and genotype (Table 1). Based on the overall means, coating increased germination percentage from 86.40% in uncoated seeds to 89.42% in coated seeds, corresponding to an increase of approximately 3.50%. In contrast, the very similar mean values recorded before storage (88.05%), after storage (88.08%), and after transportation (87.60%) indicated that germination percentage was generally maintained throughout the process. However, the coating × storage interaction showed a different pattern. Germination percentage in uncoated seeds decreased from 87.25% before storage to 85.25% after transportation, whereas it increased in coated seeds from 88.85% to 89.95%. Consequently, the difference between coated and uncoated seeds increased from 1.60 percentage points before storage to 4.70 percentage points after transportation. These results indicate that although storage alone did not significantly affect germination, coating may help maintain germination percentage, particularly during the transportation stage after storage (Table 2).

Marked differences were observed among cultivars in their responses to coating and storage. Based on the overall means, Icon (91.38%) and Bolton (90.71%) recorded the highest germination percentages, followed by Blue Ace (89.38%), Bilensoy (84.58%), and Sunter (83.50%). The effect of coating also varied among genotypes. Compared with uncoated seeds, coating increased germination percentage by approximately 5.05% in Bilensoy, 4.47% in Blue Ace, 4.58% in Icon, and 4.91% in Sunter, but decreased it by 1.18% in Bolton. Regarding the cultivar × storage interaction, Icon and Bolton maintained high germination percentages throughout the experimental stages, whereas Sunter exhibited a more pronounced reduction, particularly after transportation. This genotypic variation became even more evident in the three-way interaction, with germination percentage ranging from 79.50 to 98.00% across treatment combinations. The highest value (98.00%) was recorded in coated Icon seeds after transportation, whereas the lowest value (79.50%) was observed in uncoated Sunter seeds at the same stage. In particular, the increase in coated Icon from 91.25% before storage to 98.00% after transportation, compared with the decrease in uncoated Sunter from 84.50% to 79.50%, demonstrates that the effect of coating under storage and transportation conditions was strongly associated with the

physiological characteristics of the cultivars. Therefore, the effect of coating on germination percentage cannot be adequately explained solely by an overall comparison between coated and uncoated seeds; the genotype × coating × storage/transportation interaction should also be considered (Table 2).

The overall increase in germination percentage associated with coating is consistent with previous studies reporting that appropriate coating materials can support seed physiological performance. Amirkhani et al. (2016, 2019) reported that appropriately formulated seed coatings could improve germination and early seedling performance, whereas Qiu et al. (2020) demonstrated that coating material and application rate are critical factors and that excessive coating may restrict water uptake and radicle emergence. Similarly, studies conducted specifically in alfalfa by Mehrabi et al. (2015), Bıçakcı et al. (2018), Süheri et al. (2019), and Öten and Tuzlacı (2024) reported that germination responses to coating treatments may vary depending on environmental conditions, coating material, and application characteristics. Sprey et al. (2025) also highlighted the importance of coating integrity, water relations, and storage stability in determining coated-seed performance, supporting the significant coating × storage interaction observed in the present study. In particular, the positive response to coating observed in Bilensoy, Blue Ace, Icon, and Sunter, compared with the slight reduction observed in Bolton, together with the 18.50-percentage-point difference between coated Icon (98.00%) and uncoated Sunter (79.50%) after transportation, clearly demonstrates that coating effectiveness is genotype-dependent. Overall, these findings indicate that high and stable germination percentage in alfalfa cannot be attributed solely to seed coating. Rather, evaluate the effectiveness of coating technologies alongside genotype and storage/transportation conditions. Particularly in genotypes that respond positively to coating, appropriate coating treatments may offer considerable potential to maintain physiological seed quality throughout commercial storage and distribution processes.

Emergence Speed

Analysis of variance revealed that emergence speed in alfalfa was significantly affected by the main effects of coating, storage stage, and cultivar, as well as by all coating × storage, cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions ($p < 0.01$) (Table 1). Based on overall means, coating increased emergence speed from 83.08% in uncoated seeds to 85.95% in coated seeds, an increase of approximately 3.45%. Across storage stages, emergence speed was highest before storage (86.28%), decreased to 84.45% after storage, and fell further to 82.83% after transportation, indicating a progressive decline throughout storage and transportation. The coating × storage interaction also showed that the advantage conferred by coating varied by storage stage. Before storage, coated seeds showed an emergence speed of 89.05%, compared with 83.50% in uncoated seeds, a difference of 5.55 percentage points. This difference decreased to 1.80 percentage points after storage (85.35 vs. 83.55%) and to 1.25 percentage points after transportation (83.45 vs. 82.20%). Furthermore, from before storage to after transportation, emergence speed decreased by approximately 1.56% in uncoated seeds and by 6.29% in coated seeds. These findings indicate that although coating increased overall emergence speed, the initial advantage diminished as storage and transportation progressed. They also suggest that emergence speed may be more sensitive to storage and transportation conditions than germination-related traits and may therefore provide a useful indicator of seed vigor (Table 2).

Marked genotypic variation was observed among cultivars for emergence speed. Based on the overall means, Icon exhibited the highest emergence speed (90.58%), followed by Blue Ace (88.96%), Bolton (86.83%), Bilensoy (79.88%), and Sunter (76.33%). However, responses to coating differed considerably among cultivars. Compared with uncoated seeds, coating increased emergence speed from 72.67 to 80.00% in Sunter, corresponding to an increase of approximately 10.09%. Similarly, emergence speed increased from 84.08 to 89.58% in Bolton (approximately 6.54%) and from 78.67 to 81.08% in Bilensoy (approximately 3.06%). In contrast, Blue Ace decreased slightly, from 89.25 to 88.67% (approximately 0.65%), and Icon decreased slightly, from 90.75 to 90.42% (approximately 0.36%). The pronounced improvement observed in Sunter, which had the lowest emergence speed under uncoated conditions, indicates that coating provided a particularly beneficial effect in this relatively low-performing genotype. The cultivar × storage interaction also revealed substantial differences in the maintenance of emergence performance during storage and transportation. Icon maintained a high emergence speed throughout the experimental stages, with mean values of 89.00% before storage, 93.25% after storage, and 89.50% after transportation. Bolton also maintained relatively high performance, with values of 88.00%, 83.25%, and 89.25%. In contrast, emergence speed decreased from

84.63% before storage to 75.00% after transportation in Bilensoy, a reduction of approximately 11.38%, while Sunter decreased from 80.75% to 74.50%, a reduction of approximately 7.74%. The three-way interaction further emphasized these genotype-specific responses. Uncoated Icon showed the highest emergence speed (96.50%) after storage, whereas uncoated Sunter showed the lowest (68.50%) after both storage and transportation. In contrast, coated Sunter maintained emergence speeds of 79.00% after storage and 80.50% after transportation. Thus, coating improved emergence performance in Sunter by 10.50 percentage points after storage and 12.00 percentage points after transportation compared with the corresponding uncoated seeds. These findings indicate that coating may help mitigate losses in emergence performance in genotypes that are particularly sensitive to storage and transportation conditions. Overall, the response to coating was not uniform across cultivars but was strongly influenced by the cultivar × coating × storage/transportation interaction (Table 2).

The overall increase in emergence speed associated with coating is largely consistent with previous studies reporting that appropriate seed-coating systems can support early seedling performance. Amirkhani et al. (2016, 2019) reported that plant protein- and biostimulant-based coating systems could improve early seedling development, while Afzal et al. (2020) indicated that modern coating technologies may promote seedling establishment by delivering biostimulants and nutrients to the seed microenvironment. Similarly, Qiu et al. (2020) showed that coating effects depend on formulation and application rate, whereas Sprey et al. (2025) emphasized that coating performance may vary substantially with the physical properties of the coating material, moisture relations, and storage conditions. Findings reported for alfalfa by Bıçakcı et al. (2018) and Süheri et al. (2019) also support the view that coating treatments' effects on early-stage performance interact with environmental conditions. In the present study, although coating increased overall emergence speed, the progressive reduction in the initial advantage of coated seeds during storage and transportation indicates that the beneficial effect observed before storage did not necessarily translate into an equivalent advantage after prolonged storage and transportation. Furthermore, the pronounced improvement observed in Sunter following coating, compared with the slight reductions observed in Icon and Blue Ace, demonstrates a strong genotypic component in the response to coating. Collectively, these findings indicate that high and stable emergence performance in alfalfa cannot be attributed solely to coated seeds; rather, cultivar, coating treatment, and storage/transportation conditions should be evaluated jointly. Appropriate coating technologies may therefore be particularly important for maintaining early seedling establishment in genotypes whose emergence performance is more susceptible to deterioration during storage and transportation.

Emergence Percentage

Analysis of variance revealed that emergence percentage in alfalfa was significantly affected by the main effects of coating, storage stage, and cultivar, as well as by all two-way and three-way interactions among these factors ($p < 0.01$) (Table 1). Based on the overall means, coating increased emergence percentage from 83.77% in uncoated seeds to 86.32% in coated seeds, corresponding to a relative increase of approximately 3.04%. In contrast, emergence percentage declined progressively during storage and transportation, decreasing from 86.95% before storage to 85.25% after storage and further to 82.93% after transportation. Thus, emergence percentage decreased by approximately 4.62% from before storage to after transportation. This trend indicates that although coating generally supported seedling establishment, storage and particularly the subsequent transportation process may lead to a progressive decline in seed vigor. The significant coating × storage interaction further shows that the advantage conferred by coating depended on storage conditions and that emergence percentage may be a sensitive trait for assessing changes in physiological seed quality throughout the commercial seed supply chain (Table 3).

Genotypic differences played a major role in determining emergence percentage. Based on the overall means, Icon exhibited the highest emergence percentage (90.88%), followed by Blue Ace (89.29%), Bolton (87.83%), Bilensoy (80.33%), and Sunter (76.88%). However, responses to coating differed considerably among cultivars. Compared with uncoated seeds, coating increased emergence percentage by about 11.83% in Sunter, 3.27% in Bolton, and 3.16% in Bilensoy, whereas Blue Ace and Icon showed slight decreases of about 0.84% and 0.45%, respectively. In particular, Sunter, which exhibited the lowest emergence percentage under uncoated conditions (72.58%), increased to 81.17% following coating, demonstrating a pronounced beneficial effect of coating in this genotype with relatively low

initial performance. Responses to storage and transportation also varied among cultivars. From before storage to after transportation, emergence percentage decreased by approximately 12.12% in Bilensoy, 6.51% in Sunter, 3.92% in Blue Ace, and 1.80% in Bolton, whereas it increased slightly, by approximately 0.71%, in Icon. These differences became even more pronounced in the three-way interaction. Uncoated Icon reached the highest emergence percentage (97.00%) after storage, whereas uncoated Sunter exhibited the lowest value (68.00%) at the same stage. In contrast, emergence percentage in coated Sunter increased from 80.25% before storage to 81.25% after storage and 82.00% after transportation, suggesting that coating may help mitigate performance losses, particularly in genotypes sensitive to storage and transportation conditions. Therefore, the effect of coating on emergence percentage should be interpreted not simply as an overall difference between coated and uncoated seeds but rather as the outcome of a strong cultivar × coating × storage/transportation interaction (Table 3).

The overall increase in emergence percentage associated with coating generally aligns with previous studies showing that appropriate coating systems can support early seedling performance. Amirkhani et al. (2016, 2019) reported that plant protein- and biostimulant-based coatings could promote early plant development, while Afzal et al. (2020) emphasized that modern seed-coating technologies can improve seedling establishment by delivering active components, such as biostimulants and nutrients, directly to the seed microenvironment. Similarly, Qiu et al. (2020) demonstrated that coating performance depends on formulation and application rate, whereas Sprey et al. (2025) reported that the physical properties of coating materials and storage conditions may determine coating effectiveness. Findings from alfalfa by Mehrabi et al. (2015), Bıçakcı et al. (2018), and Öten and Tuzlacı (2024) also support the view that early-stage responses to coating treatments vary with application characteristics and environmental conditions. In the present study, the 11.83% increase in emergence percentage following coating in Sunter, along with the absence of the pronounced post-storage decline observed in uncoated Sunter seeds, suggests that coating benefits may be more pronounced in genotypes with lower initial performance or greater sensitivity to storage stress. In contrast, Icon's ability to maintain a high emergence percentage regardless of coating suggests that the genotype's intrinsic vigor may influence the magnitude of the response to coating. Collectively, these findings show that high and stable emergence percentage in alfalfa cannot be ensured solely through coated seeds. Instead, cultivar, coating treatment, and storage/transportation conditions should be jointly optimized, and appropriate coating technologies may play a particularly important role in maintaining seedling establishment in genotypes susceptible to performance losses during storage.

Number of Normal Seedlings

Analysis of variance revealed that the number of normal seedlings in alfalfa was significantly affected by the main effects of coating, storage stage, and cultivar, as well as by all two-way and three-way interactions among these factors ($p < 0.01$) (Table 1). Based on the overall means, coating increased the number of normal seedlings from 91.03 in uncoated seeds to 91.83 in coated seeds, corresponding to a modest increase of approximately 0.88%. In contrast, the number of normal seedlings decreased from 93.28 before storage to 90.68 after storage and 90.35 after transportation, representing reductions of approximately 2.79% and 3.14%, respectively, relative to the pre-storage value. The coating × storage interaction indicated that the effect of coating became particularly relevant after storage. At this stage, coated seeds maintained 91.75 normal seedlings, compared with 89.60 in uncoated seeds. In contrast, before storage, uncoated and coated seeds produced 93.20 and 93.35 normal seedlings, respectively, and belonged to the same statistical group, while after transportation the corresponding values converged to 90.30 and 90.40. These results indicate that the protective effect of coating was not consistent across all stages. Therefore, despite the relatively small overall effect of coating, its ability to reduce losses in the number of normal seedlings after storage may be a more biologically and technologically meaningful benefit for maintaining commercial seed quality (Table 3).

Marked differences among cultivars were observed in their capacity to produce normal seedlings. Based on the overall means, Blue Ace exhibited the highest number of normal seedlings (93.46), followed by Icon (92.25) and Bolton (91.96), whereas Bilensoy (90.29) and particularly Sunter (89.21) exhibited lower values. However, both the direction and magnitude of the response to coating differed substantially among cultivars. Coating increased the number of normal seedlings in Sunter from 86.58 to 91.83, corresponding to a pronounced increase of approximately 6.06%. More modest increases of

approximately 1.02% and 0.82% were observed in Bilensoy and Bolton, respectively, whereas decreases of approximately 0.62% and 2.50% were observed in Blue Ace and Icon, respectively. The cultivar × storage interaction also demonstrated that genotypes differed in their ability to maintain normal seedling production during storage and transportation. Blue Ace maintained a high number of normal seedlings before and after storage, whereas Icon exhibited a relatively high value of 93.13 after transportation. In contrast, Bilensoy declined from 94.88 before storage to 86.63 after transportation. The three-way interaction further highlighted this genotypic variation, with values ranging from 80.00 to 97.00 normal seedlings across treatment combinations. The highest value (97.00) was recorded for coated Blue Ace before storage, whereas the lowest value (80.00) was observed for uncoated Sunter after storage. Notably, while the number of normal seedlings in uncoated Sunter decreased to 80.00 after storage, coated Sunter remained at 92.00, a difference of 12 seedlings. This finding demonstrates that coating substantially limited storage-related losses in this genotype. Consequently, evaluation of the overall coating mean alone may mask strong genotype-specific responses, emphasizing the importance of assessing coating effectiveness within the context of cultivar × storage interactions (Table 3).

Table 3. Mean emergence percentage (%), number of normal seedlings, and number of abnormal seedlings of alfalfa cultivars under different coating treatments and storage stages, with statistical groupings.

Coating	Storage	Cultivars					Mean
		Bilensoy	Blue Ace	Bolton	Icon	Sunter	
Emergence Percentage (%)							
Uncoated	Before	81,25^{k}	88,00^{fg}	88,25^{efg}	85,00^{hi}	81,00^{kl}	84,70^{c}
	After	78,75^{lm}	93,75^{b}	84,25^{ij}	97,00^{a}	68,00^{o}	84,35^{cd}
	Transportation	77,25^{m}	87,25^{gh}	86,75^{gh}	91,25^{cd}	68,75^{o}	82,25^{e}
	Mean	79,08^{f}	89,67^{bc}	86,42^{d}	91,08^{a}	72,58^{g}	83,77
Coated	Before	90,00^{def}	90,50^{de}	92,25^{bcd}	93,00^{bcd}	80,25^{kl}	89,20^{a}
	After	81,50^{k}	92,00^{bcd}	85,00^{hi}	91,00^{cd}	81,25^{k}	86,15^{b}
	Transportation	73,25^{n}	84,25^{ij}	90,50^{de}	88,00^{fg}	82,00^{jk}	83,60^{d}
	Mean	81,58^{e}	88,92^{c}	89,25^{c}	90,67^{ab}	81,17^{e}	86,32
Mean	Before	85,63^{d}	89,25^{bc}	90,25^{b}	89,00^{bc}	80,63^{e}	86,95^{a}
	After	80,13^{e}	92,88^{a}	84,63^{d}	94,00^{a}	74,63^{f}	85,25^{b}
	Transportation	75,25^{f}	85,75^{d}	88,63^{c}	89,63^{bc}	75,38^{f}	82,93^{c}
	Mean	80,33^{d}	89,29^{b}	87,83^{c}	90,88^{a}	76,88^{e}	85,04
Number of Normal Seedlings							
Uncoated	Before	96,00^{ab}	95,00^{abc}	90,00^{h-k}	91,00^{f-i}	94,00^{b-e}	93,20^{a}
	After	88,50^{jk}	92,50^{d-g}	92,00^{e-h}	95,00^{abc}	80,00^{m}	89,60^{d}
	Transportation	85,00^{l}	93,75^{b-e}	92,75^{c-f}	94,25^{b-e}	85,75^{l}	90,30^{cd}
	Mean	89,83^{e}	93,75^{a}	91,58^{cd}	93,42^{ab}	86,58^{f}	91,03
Coated	Before	93,75^{b-e}	97,00^{a}	94,75^{a-d}	90,50^{f-k}	90,75^{f-j}	93,35^{a}
	After	90,25^{g-k}	93,75^{b-e}	92,00^{e-h}	90,75^{f-j}	92,00^{e-h}	91,75^{b}
	Transportation	88,25^{k}	88,75^{ijk}	90,25^{g-k}	92,00^{e-h}	92,75^{c-f}	90,40^{c}
	Mean	90,75^{de}	93,17^{ab}	92,33^{bc}	91,08^{d}	91,83^{cd}	91,83
Mean	Before	94,88^{a}	96,00^{a}	92,38^{bcd}	90,75^{ef}	92,38^{bcd}	93,28^{a}
	After	89,38^{f}	93,13^{b}	92,00^{b-e}	92,88^{bc}	86,00^{g}	90,68^{b}
	Transportation	86,63^{g}	91,25^{de}	91,50^{cde}	93,13^{b}	89,25^{f}	90,35^{b}
	Mean	90,29^{c}	93,46^{a}	91,96^{b}	92,25^{b}	89,21^{d}	91,43
Number of Abnormal Seedlings							
Uncoated	Before	1,75^{ij}	1,75^{ij}	1,50^{j}	2,50^{g-j}	2,00^{ij}	1,90^{d}
	After	5,00^{de}	2,00^{ij}	2,75^{g-j}	2,75^{g-j}	4,75^{def}	3,45^{b}
	Transportation	8,00^{b}	3,25^{f-i}	4,50^{def}	3,75^{e-h}	6,75^{bc}	5,25^{a}
	Mean	4,92^{a}	2,33^{cd}	2,92^{bcd}	3,00^{bcd}	4,50^{a}	3,53
Coated	Before	2,25^{hij}	1,25^{j}	2,25^{hij}	4,00^{efg}	2,75^{g-j}	2,50^{c}

	After	3,75^{e-h}	2,50^{g-j}	2,25^{hij}	2,25^{hij}	4,75^{def}	3,10^{b}
	Transportation	9,75^{a}	5,75^{cd}	2,25^{hij}	4,50^{def}	1,75^{ij}	4,80^{a}
	Mean	5,25^{a}	3,17^{b}	2,25^{d}	3,58^{b}	3,08^{bc}	3,47
Mean	Before	2,00^{g}	1,50^{g}	1,88^{g}	3,25^{def}	2,38^{efg}	2,20^{c}
	After	4,38^{bc}	2,25^{fg}	2,50^{efg}	2,50^{efg}	4,75^{b}	3,28^{b}
	Transportation	8,88^{a}	4,50^{b}	3,38^{cde}	4,13^{bcd}	4,25^{bcd}	5,03^{a}
	Mean	5,08^{a}	2,75^{d}	2,58^{d}	3,29^{c}	3,79^{b}	3,50

[1]Means followed by the same letter are not significantly different.

The results show that the effect of seed coating on normal seedling production depended on storage conditions and genotypic characteristics rather than providing a direct, uniform improvement across all genotypes. Amirkhani et al. (2019) reported that appropriate coating components could support early plant development, whereas Qiu et al. (2020) showed that the effectiveness of biostimulant-containing coatings on germination and seedling establishment may vary by coating formulation and plant material. Afzal et al. (2020) also emphasized that modern coating technologies can support seedling establishment by delivering active compounds to the seed microenvironment. Furthermore, the variable responses to application and environmental conditions reported in alfalfa by Bıçakcı et al. (2018) and Öten and Tuzlacı (2024) are consistent with the strong cultivar × coating × storage interaction observed in the present study. In this context, Blue Ace showed the highest overall capacity for normal seedling production but gained no additional benefit from coating, whereas coating improved the number of normal seedlings by approximately 6.06% in Sunter, which had lower initial performance. More importantly, the 12-seed difference between uncoated and coated Sunter after storage shows that, beyond the modest overall coating effect of only 0.88%, coating may provide substantial protection in genotypes sensitive to storage-related deterioration. Overall, these findings indicate that high and stable production of normal seedlings in alfalfa cannot be ensured solely through coated seeds. Rather, evaluate the effectiveness of coating technologies alongside genotype and storage/transportation conditions, and develop genotype-specific coating strategies, particularly for cultivars susceptible to storage-induced vigor losses.

Number of Abnormal Seedlings

Analysis of variance revealed that the number of abnormal seedlings in alfalfa was significantly affected by the main effects of storage stage and cultivar ($p < 0.01$), whereas the main effect of coating was not statistically significant. However, all coating × storage, cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions were significant ($p < 0.01$), demonstrating that the effect of coating on abnormal seedling formation was neither direct nor uniform but varied depending on genotype and storage stage (Table 1). Based on the overall means, coating reduced the number of abnormal seedlings only slightly, from 3.53 in uncoated seeds to 3.47 in coated seeds, corresponding to a reduction of approximately 1.70%. In contrast, the number of abnormal seedlings increased from 2.20 before storage to 3.28 after storage and 5.03 after transportation, representing increases of 49.09% and 128.64%, respectively, relative to the pre-storage value. The coating × storage interaction also showed that this trend differed by coating status. From before storage to after transportation, the number of abnormal seedlings increased from 1.90 to 5.25 in uncoated seeds (176.32%), whereas it increased from 2.50 to 4.80 in coated seeds (92.00%). Thus, although coating did not reduce abnormal seedling formation before storage, it partially limited the increase after storage and transportation. This finding suggests that the potential protective effect of coating may become more evident after seeds are exposed to storage and transportation processes (Table 3).

Marked genotypic variation was observed in abnormal seedling formation. Based on the overall means, Bilensoy exhibited the highest number of abnormal seedlings (5.08), followed by Sunter (3.79) and Icon (3.29), whereas Blue Ace (2.75) and Bolton (2.58) exhibited the lowest values. However, the response direction to coating differed substantially among cultivars. Coating increased the number of abnormal seedlings by approximately 6.71% in Bilensoy, 36.05% in Blue Ace, and 19.33% in Icon, whereas Bolton and Sunter showed reductions of approximately 22.95% and 31.56%, respectively. The response observed in Sunter was particularly noteworthy, indicating that coating may substantially reduce abnormal seedling formation in this cultivar. The cultivar × storage interaction also revealed differences in physiological stability among genotypes throughout storage and transportation. After transportation,

Bilensoy exhibited the highest number of abnormal seedlings (8.88), whereas Bolton had the lowest value (3.38). The three-way interaction further emphasized the magnitude of these genotype-specific responses, with the number of abnormal seedlings ranging from 1.25 to 9.75 across treatment combinations. The highest value (9.75) was recorded for coated Bilensoy after transportation, whereas the lowest value (1.25) was observed for coated Blue Ace before storage. More importantly, after transportation, the number of abnormal seedlings in Sunter decreased from 6.75 in uncoated seeds to 1.75 in coated seeds, showing that coating strongly mitigated the adverse effects of transportation in this cultivar. In contrast, at the same stage, coated Bilensoy produced 9.75 abnormal seedlings compared with 8.00 in uncoated seeds. This contrasting response shows that coating did not protect all genotypes and that the overall coating mean may mask opposing cultivar-specific responses (Table 3).

The marked increase in abnormal seedlings after storage, and particularly transportation, suggests that changes in seed physiological quality during these processes may impair normal seedling development. Considering that seed aging is associated with deterioration of membrane integrity, alterations in metabolic and enzymatic activities, and reductions in cellular repair capacity, the present findings are generally consistent with those of Čupić et al. (2005) and Behtari et al. (2014), who reported that storage and aging can affect seed quality in alfalfa. Although the main effect of coating was not significant, the lower number of abnormal seedlings observed in coated seeds after storage and transportation indicates that coating effectiveness should be evaluated in interaction with storage conditions. Pedrini et al. (2017) emphasized that the effects of coating technologies on seedling establishment may vary depending on coating material and environmental conditions, while findings reported in alfalfa by Bıçakcı et al. (2018), Arslan et al. (2020), and Öten and Tuzlacı (2024) similarly demonstrated that early seedling responses to coating treatments may differ according to application and stress conditions. In the present study, the reduction in abnormal seedling formation following coating in Sunter and Bolton, compared with the increases observed in Bilensoy, Blue Ace, and Icon, is particularly important and demonstrates that coating technology should not be considered a genotype-independent, universally beneficial treatment. Overall, the findings indicate that abnormal seedling formation was determined primarily by storage/transportation conditions and genotypic characteristics rather than by the independent effect of coating. Coating, in turn, could exert either protective or adverse effects through its interactions with these factors. Therefore, optimization of coating technologies in alfalfa should consider not only mean seedling performance but also genotype-specific variation in abnormal seedling formation following storage and transportation as an important criterion of seed vigor and physiological quality.

Number of Hard Seeds

Analysis of variance revealed that the number of hard seeds in alfalfa was significantly affected by the main effects of coating, storage stage, and cultivar ($p < 0.01$). The cultivar × coating and cultivar × coating × storage interactions were also significant ($p < 0.01$), whereas the coating × storage and cultivar × storage interactions were not significant, indicating that the effect of coating varied primarily according to genotype (Table 1). Based on the overall means, the number of hard seeds decreased from 0.93 in uncoated seeds to 0.58 in coated seeds, corresponding to a reduction of approximately 37.63%. Across storage stages, the number of hard seeds decreased from 0.98 before storage to 0.58 after storage, representing a reduction of approximately 40.82%. Although the value subsequently increased to 0.73 after transportation, it remained approximately 25.51% below the pre-storage level. These findings indicate that both coating and storage may reduce hardseededness. However, because the coating × storage interaction was not significant, the results do not support the conclusion that these two factors systematically modified each other's effects. Therefore, the most notable finding regarding hardseededness was not simply the overall reduction associated with coating, but rather the genotype-dependent variation in this response (Table 4).

Cultivars showed marked variation in the number of hard seeds. Bolton exhibited the highest overall value (1.67), followed by Icon (0.92), Blue Ace and Sunter (0.54 each), whereas Bilensoy exhibited the lowest number of hard seeds (0.13). The significant cultivar × coating interaction further demonstrated that both the direction and magnitude of the coating response varied among genotypes. Coating markedly reduced hard seeds in Bolton (2.25 to 1.08) and Icon (1.33 to 0.50), while Bilensoy showed a smaller reduction (0.17 to 0.08). In contrast, coating increased hard seeds from 0.42 to 0.67 in Blue Ace and from 0.50 to 0.58 in Sunter. The significant three-way interaction further confirmed differential genotype responses to coating and storage, with values ranging from 0.00 to 2.25 hard seeds across treatment combinations. Notably, the number of hard seeds in uncoated Bolton remained constant at

2.25 before storage, after storage, and after transportation, whereas in coated Bolton it decreased from 2.25 before storage to 0.25 after storage and 0.75 after transportation. In contrast, no hard seeds were recorded for uncoated Bilensoy after transportation, coated Bilensoy before and after storage, or coated Icon after transportation. These findings suggest that in genotypes with a relatively high tendency toward hardseededness, such as Bolton, coating may have greater potential to reduce the number of hard seeds following storage. However, because the same response was not observed in genotypes such as Blue Ace and Sunter, evaluate the effects of coating on a genotype-specific basis (Table 4).

Hardseededness is a major manifestation of physical dormancy in legumes, characterized by seed-coat impermeability to water and gases, and can directly influence the initiation of germination and the temporal uniformity of seedling establishment in alfalfa. Galussi et al. (2015) reported that hardseededness in alfalfa is closely associated with seed-coat structural characteristics, and the marked difference observed between Bolton and Bilensoy in the present study further supports a strong genotypic component underlying this trait. The decrease in the number of hard seeds from 0.98 before storage to 0.58 after storage also aligns with Čupić et al. (2005), who reported that the proportion of hard seeds in alfalfa may decline as storage duration increases. Although coating reduced the overall number of hard seeds by approximately 37.63%, suggesting that the coating process may alter seed-surface processes and water uptake, the present experimental data do not directly establish the physiological mechanism underlying this reduction. Therefore, attributing the observed effect solely to changes in seed-coat permeability would not be justified. More importantly, the pronounced reductions observed in Bolton and Icon, compared with the slight increases observed in Blue Ace and Sunter, demonstrate that the effect of coating on physical dormancy was genotype-dependent. Overall, these findings indicate that genotype strongly influences hardseededness, while coating and storage can further modify this trait. Consequently, seed technologies aimed at achieving rapid and uniform seedling establishment in alfalfa should consider not only the overall effect of coating but also cultivar-specific levels of hardseededness and their changes during storage following coating.

Table 4. Mean number of hard seeds and dead seeds of alfalfa cultivars under different coating treatments and storage stages, with statistical groupings.

Coating	Storage	Cultivars					Mean
		Bilensoy	Blue Ace	Bolton	Icon	Sunter	
Number of Hard Seeds							
Uncoated	Before	0,25^{bc}	0,75^{abc}	2,25^{a}	1,25^{abc}	0,75^{abc}	1,05
	After	0,25^{bc}	0,25^{bc}	2,25^{a}	1,00^{abc}	0,25^{bc}	0,80
	Transportation	0,00^{c}	0,25^{bc}	2,25^{a}	1,75^{ab}	0,50^{bc}	0,95
	Mean	0,17^{d}	0,42^{cd}	2,25^{a}	1,33^{b}	0,50^{cd}	0,93
Coated	Before	0,00^{c}	0,25^{bc}	2,25^{a}	0,75^{abc}	1,25^{abc}	0,90
	After	0,00^{c}	0,50^{bc}	0,25^{bc}	0,75^{abc}	0,25^{bc}	0,35
	Transportation	0,25^{bc}	1,25^{abc}	0,75^{abc}	0,00^{c}	0,25^{bc}	0,50
	Mean	0,08^{d}	0,67^{bcd}	1,08^{bc}	0,50^{cd}	0,58^{cd}	0,58
Mean	Before	0,13	0,50	2,25	1,00	1,00	0,98^{a}
	After	0,13	0,38	1,25	0,88	0,25	0,58^{b}
	Transportation	0,13	0,75	1,50	0,88	0,38	0,73^{ab}
	Mean	0,13^{c}	0,54^{bc}	1,67^{a}	0,92^{b}	0,54^{bc}	0,76
Number of Dead Seeds							
Uncoated	Before	2,00^{i-n}	2,50^{h-n}	6,25^{b-e}	5,25^{b-h}	3,25^{f-m}	3,85^{bcd}
	After	6,25^{b-e}	5,25^{b-h}	3,00^{g-n}	1,25^{k-n}	15,00^{a}	6,15^{a}
	Transportation	7,00^{bc}	2,50^{h-n}	0,50^{mn}	0,25^{n}	7,25^{b}	3,50^{cd}
	Mean	5,08^{b}	3,42^{cde}	3,25^{cde}	2,25^{e}	8,50^{a}	4,50
Coated	Before	4,00^{d-k}	1,50^{j-n}	0,75^{lmn}	4,75^{b-i}	5,25^{b-h}	3,25^{d}
	After	6,00^{b-f}	3,25^{f-m}	5,50^{b-g}	6,25^{b-e}	3,00^{g-n}	4,80^{b}
	Transportation	1,75^{j-n}	4,25^{c-j}	6,75^{bcd}	3,50^{e-l}	5,25^{b-h}	4,30^{bc}
	Mean	3,92^{bcd}	3,00^{de}	4,33^{bcd}	4,83^{b}	4,50^{bc}	4,12
Mean	Before	3,00^{efg}	2,00^{fg}	3,50^{d-g}	5,00^{bcd}	4,25^{de}	3,55^{b}
	After	6,13^{bc}	4,25^{de}	4,25^{de}	3,75^{def}	9,00^{a}	5,48^{a}

	Transportation	4,38^{cde}	3,38^{d-g}	3,63^{d-g}	1,88^{g}	6,25^{b}	3,90^{b}
	Mean	4,50^{b}	3,21^{c}	3,79^{bc}	3,54^{c}	6,50^{a}	4,31

[1]Means followed by the same letter are not significantly different.

Number of Dead Seeds

Analysis of variance revealed that the number of dead seeds in alfalfa was significantly affected by the main effects of storage stage and cultivar ($p < 0.01$), whereas the main effect of coating was not statistically significant. However, all coating × storage, cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions were significant ($p < 0.01$), showing that the effect of coating on seed viability depended on genotype and storage stage rather than being direct and broadly generalizable (Table 1). Based on the overall means, the number of dead seeds was 4.50 in uncoated seeds and 4.12 in coated seeds, corresponding to a numerical reduction of approximately 8.44% following coating. However, because the main effect of coating was not statistically significant, this numerical difference should not be interpreted as a general advantage of coating. In contrast, storage stage had a pronounced effect. The number of dead seeds increased from 3.55 before storage to 5.48 after storage, representing an increase of approximately 54.37%, and subsequently decreased to 3.90 after transportation, approaching the pre-storage level. The significant coating × storage interaction also showed that this response differed by coating status. After storage, the number of dead seeds was 6.15 in uncoated seeds compared with 4.80 in coated seeds, suggesting that coating may have limited seed mortality at this stage. In contrast, after transportation, coated seeds exhibited a higher value than uncoated seeds (4.30 vs. 3.50). These findings demonstrate that the effect of coating on the maintenance of seed viability was not consistent throughout the experimental stages and that its effects should therefore be evaluated according to storage stage rather than solely on the basis of overall means (Table 4).

Marked genotypic variation was observed in the number of dead seeds. Based on the overall means, Sunter exhibited the highest value (6.50), followed by Bilensoy (4.50), Bolton (3.79), Icon (3.54), and Blue Ace (3.21). However, the significant cultivar × coating interaction demonstrated that responses to coating were more complex than the overall cultivar means alone would suggest. Coating reduced the number of dead seeds by approximately 22.83% in Bilensoy, 12.28% in Blue Ace, and 47.06% in Sunter, whereas it increased the number of dead seeds by approximately 33.23% and 114.67% in Bolton and Icon, respectively. The high F-value for the three-way interaction ($F = 47.082$) further indicates that these genotype-specific responses became more pronounced across storage stages. The treatment combinations exhibited a wide range of variation, from 0.25 to 15.00 dead seeds. The highest number of dead seeds (15.00) was recorded for uncoated Sunter after storage, whereas the lowest value (0.25) was observed for uncoated Icon after transportation. Notably, Sunter after storage showed 15.00 dead seeds in uncoated seeds but only 3.00 in coated seeds, indicating that coating markedly limited storage-associated seed mortality in this cultivar. In contrast, coating increased the overall number of dead seeds in Icon from 2.25 to 4.83, demonstrating that the same treatment may produce contrasting responses among cultivars. Therefore, the effectiveness of coating technologies should not be reduced to a simple coated-versus-uncoated comparison but should instead be evaluated within the context of cultivar × coating × storage interactions (Table 4).

The marked increase in dead seeds after storage suggests that seeds underwent physiological deterioration during storage and that viability losses were sensitive to storage conditions. Seed aging has been associated with deterioration of membrane integrity, reductions in metabolic and enzymatic activity, and the accumulation of oxidative damage, processes that may ultimately reduce seed viability and germination ability (McDonald, 1999; Walters et al., 2010). Similarly, seed longevity depends not only on environmental conditions but also on genetic background, initial seed quality, and seed moisture content (Walters et al., 2004; Rajjou and Debeaujon, 2008; Rajjou et al., 2012). In this context, the higher number of dead seeds observed in Sunter, together with the pronounced loss of viability in its uncoated seeds after storage, supports substantial cultivar-specific differences in storage tolerance. Although coating markedly limited this loss in Sunter, the increases in dead seeds observed in Bolton and Icon indicate that coating did not provide a uniform protective effect across cultivars. This genotype-dependent response is consistent with Pedrini et al. (2017), who argue that the physical and chemical properties of coating materials may alter water and gas exchange in the seed microenvironment, potentially resulting in beneficial, neutral, or adverse effects depending on the seed and coating system.

Overall, the findings indicate that genotype is an important determinant of seed viability maintenance during storage in alfalfa and that coating should not be regarded as a universally protective strategy. Instead, coating formulations should be optimized according to genotype-specific storage tolerance, and identifying cultivar × coating combinations that effectively limit dead seed formation after storage may provide a more rational approach to maintaining commercial seed quality.

CONCLUSION

This study showed that the effects of seed coating, storage, and transportation on the physiological quality of alfalfa seeds largely depended on cultivar and the specific seed quality trait evaluated. Overall, seed coating improved germination speed and germination percentage, and the smaller performance losses in coated seeds compared with uncoated seeds after transportation suggest that appropriate coating treatments may help maintain germination performance throughout the commercial storage and distribution chain. In contrast, the progressive reductions in emergence speed and emergence percentage during storage and transportation indicate that seed vigor may be more sensitive to environmental and physical stresses associated with these processes, even when germination percentage remains relatively stable. The reduction in normal seedlings, along with increases in abnormal seedlings and dead seeds, further shows that storage and transportation effects on physiological seed quality cannot be assessed based on germination percentage alone. Marked differences were observed among cultivars: Icon and Bolton generally performed well for germination and emergence traits, Blue Ace was distinguished by its high capacity to produce normal seedlings, whereas Sunter showed lower and more variable performance for several traits. Nevertheless, the improved emergence and normal seedling production and the marked reduction in dead seed formation after storage observed in coated Sunter seeds, together with the limited or adverse responses to coating observed in some other cultivars, clearly demonstrate that coating does not provide a universal, genotype-independent advantage. In particular, the significance of cultivar × coating × storage/transportation interactions for most of the evaluated traits indicates that the effectiveness of coating technologies in commercial alfalfa seed production should be assessed not only on the basis of initial germination performance but also according to their capacity to maintain seed vigor and viability after storage and transportation. Overall, maintaining high and stable seed quality requires genotype-specific optimization of coating formulations and storage and transportation protocols. An integrated assessment of germination, emergence, normal seedling development, and viability losses is therefore recommended as a fundamental approach for improving the effectiveness and reliability of coated alfalfa seeds under commercial conditions.

ACKNOWLEDGMENTS

This study was supported by the Scientific Research Projects Coordination Unit of Selçuk University under Project No. 25201029. This study was prepared as part of the M.Sc. thesis conducted by Muhammed Emin EROL at the Department of Field Crops, Graduate School of Natural and Applied Sciences, Selçuk University.

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RESPONSE OF GERMINATION PERFORMANCE TO SEED COATING, STORAGE, AND TRANSPORTATION IN SUGAR BEET CULTIVARS

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ABSTRACT
Rapid, high germination is a fundamental component of seed quality in sugar beet, as it contributes to uniform crop establishment and optimal plant density. This study aimed to determine the effects of seed coating, storage, and transportation processes on the germination performance of different sugar beet cultivars. Uncoated and coated seeds of five cultivars, namely Balboa, Gregoria, Juncal, Preziosa, and Terranova, were used. Seeds were evaluated before storage, after approximately six months of storage at 5 °C and 60% relative humidity, and following a subsequent 16-h transportation period. Germination rate and germination percentage were used as the principal indicators of physiological seed performance. Analysis of variance revealed that coating, storage, cultivar, and their interactions significantly affected germination performance. Overall, germination rate decreased from 85.67% in uncoated seeds to 69.92% in coated seeds, corresponding to a reduction of approximately 18.38% due to coating. Among the cultivars, Terranova had the highest germination rate (83.54%), while Balboa had the lowest (69.21%). Similarly, germination percentage declined from 95.62% in uncoated seeds to 78.93% in coated seeds, representing a reduction of approximately 17.45%. Mean germination percentage was 92.50% before storage, decreased to 83.70% after storage, and partially recovered to 85.63% after transportation. Terranova (93.88%) and Gregoria (89.71%) maintained comparatively high germination performance, whereas Balboa had the lowest mean value (80.58%). The pronounced cultivar-specific responses to coating demonstrated that germination performance was strongly influenced by genotype × seed processing × storage interactions. In conclusion, seed coating and storage protocols should be optimized on a cultivar-specific basis to preserve high germination performance in commercial sugar beet seed production.
Keywords: Germination Percentage, Germination Rate, Seed Coating, Storage, Transportation.

INTRODUCTION
Sugar beet (*Beta vulgaris* L.) is one of the principal raw materials of the sugar industry, and the establishment of a rapid and uniform plant stand is of critical importance for achieving economically viable and sustainable production. Because plant losses after sowing in sugar beet cannot be adequately compensated for, using seeds with high physiological quality is a fundamental factor directly affecting successful crop establishment and subsequent production performance (Kockelmann and Meyer, 2006; Kockelmann et al., 2010). Therefore, seed quality assessment should consider not only final germination percentage but also traits reflecting germination speed and uniformity. In particular, germination speed and germination capacity are regarded as important indicators of seed vigor and the ability of seeds to germinate under varying environmental conditions (Finch-Savage and Bassel, 2016; Podlaski and Chomontowski, 2020). Indeed, sugar beet seed lots with similar final germination percentages may differ substantially in terms of germination speed and uniformity (Podlaski and Chomontowski, 2020). The germination performance of sugar beet seeds depends on the combined effects of numerous factors, including genotype, conditions during seed development and maturation, harvest timing, initial physiological quality, seed-processing practices, and storage conditions (Finch-Savage and Bassel, 2016; Leprince et al., 2016). In particular, environmental conditions experienced during seed development and maturation may influence seed dormancy, vigor, germination speed, and storage potential (Mirzaei and Hemayati, 2022). In sugar beet, harvest maturity and seed moisture content have been reported to play decisive roles in germination capacity and storability, whereas unfavorable storage

conditions may accelerate seed deterioration and consequently reduce germination performance (Śliwińska et al., 1999; Śliwińska, 2003). During storage, temperature, relative humidity, and seed moisture content are among the major determinants of the rate of seed aging, while appropriate storage conditions contribute to the prolonged maintenance of seed viability and vigor (Walters et al., 2005; Gürel, 2020; Solberg et al., 2020; Zinsmeister et al., 2020).

In modern sugar beet production, seeds are commonly coated or pelleted to provide standardized physical characteristics suitable for precision sowing and to enable controlled application of various active ingredients onto the seed surface (Rocha et al., 2019; Afzal et al., 2020). However, the physical and physicochemical properties of coating materials may affect seed water uptake and gas exchange, thereby modifying the initiation and progression of germination. In particular, excessive mechanical resistance of the coating layer, insufficient porosity, or inappropriate water permeability may delay imbibition and radicle emergence, ultimately reducing germination speed (Afzal et al., 2020; Ma et al., 2022). In addition to the physical properties of the pericarp, the presence of germination-inhibiting compounds such as phenolic substances, abscisic acid, and various ions in sugar beet seeds further increases the importance of interactions between the seed and coating material (Duan and Burris, 1997; Ignatz et al., 2019). Furthermore, the mechanical strength, porosity, water resistance, and chemical properties of pellets have been reported to substantially influence germination performance, particularly under suboptimal moisture conditions (Podlaski et al., 2019).

Maintaining germination performance in coated seeds until sowing depends not only on the quality of the coating process but also on the conditions encountered during storage and transportation. Physiological deterioration during storage may reduce germination speed and seed vigor before any detectable loss in final viability occurs; therefore, germination speed is a sensitive indicator of early storage-related deterioration in seed quality (Solberg et al., 2020; Zinsmeister et al., 2020). In coated seeds, maintaining coating integrity is also critical in addition to providing appropriate storage conditions. Binder and filler characteristics, along with drying conditions, can affect coating stability, water permeability, and disintegration behavior (Afzal et al., 2020; Paravar et al., 2023; Köhl et al., 2024). Moreover, vibration, friction, and mechanical stresses encountered during transportation may alter coating structure and subsequently influence seed water uptake and germination behavior. Consequently, coating, storage, and transportation should not be considered independent processes but rather sequential factors that collectively determine seed germination performance from seed processing to sowing.

Previous studies on sugar beet have demonstrated the effects of coating and pelleting characteristics, priming, polishing and washing treatments, and storage conditions on seed germination performance (Duan and Burris, 1997; Capron et al., 2000; Marcinek et al., 2011; Ignatz et al., 2019; Podlaski et al., 2019; Chomontowski et al., 2020; Gürel, 2020). Nevertheless, studies simultaneously evaluating the sequential effects of coating, storage, and transportation on the germination characteristics of different sugar beet cultivars remain limited. Furthermore, genetic and physiological differences among cultivars suggest that their responses to coating, storage, and transportation processes may be genotype-dependent. Accordingly, the present study aimed to compare germination speed and germination capacity of uncoated and coated seeds from different sugar beet cultivars before storage, after storage, and after storage plus transportation, and to determine cultivar × coating × storage/transportation interactions. The study therefore sought to elucidate both the individual and combined effects of coating and storage/transportation processes on the germination performance of commercial sugar beet seeds and to provide a scientific basis for practices aimed at preserving seed quality until sowing.

MATERIALS AND METHODS

Material

The study was conducted between 2024 and 2025 in the laboratories of the Ankara Seed Registration and Certification Directorate to determine the viability and early seedling growth performance of uncoated and coated sugar beet (*Beta vulgaris* L.) seeds before storage, after storage, and after storage plus transportation. Seeds of five sugar beet cultivars, namely Balboa, Gregoria, Juncal, Preziosa, and Terranova, were used as plant material. To enable a direct comparison of the coating treatment, seeds from the same seed lot of each cultivar were divided into two groups: coated and uncoated. Seed coating was performed by ABEL Ziraat A.Ş. at a 1:1 (w/w) ratio, corresponding to the application of 1 kg of coating material per 1 kg of seed. The cultivars used in the study differed in their agronomic

characteristics and disease tolerance. Balboa is characterized by its monogerm and root-sugar type and tolerance to *Rhizomania*; Gregoria by high resistance to *Rhizomania* and tolerance to *Cercospora* and powdery mildew; Juncal by its monogerm and root-sugar type, *Fusarium* tolerance, and suitability for early sowing; Preziosa by high resistance to *Rhizomania* and tolerance to cyst nematodes and *Cercospora*; and Terranova by high resistance to *Rhizomania* and tolerance to *Cercospora* and powdery mildew. In addition, Balboa and Juncal achieved mean root yields of 8.8 and 7.88 t ha^{-1}, respectively, in registration trials, with sugar contents of 17.10% for Balboa and 15.35% for Juncal. Thus, cultivars with different genetic and agronomic characteristics enabled cultivar-specific comparisons of responses to coating, storage, and transportation.

Methods

Germination performance before storage

To determine pre-storage germination performance, seeds were taken from harvested plants that had not yet undergone storage or transportation. Standard germination tests were conducted in accordance with the rules of the International Seed Testing Association (ISTA) to determine the initial physiological quality of the seeds. Germination speed, germination capacity, emergence speed, emergence capacity, number of normal seedlings, and number of dead seeds were determined. We used these values as baseline data to evaluate changes after storage and transportation (ISTA, 2025).

Germination performance after storage

To determine the effects of storage on seed viability and early seedling development, the seeds were stored for approximately six months at +5 °C and 60% relative humidity. At the end of the storage period, the physiological quality characteristics of the seeds were reassessed in accordance with ISTA rules. Standard germination tests were conducted, and germination speed, germination capacity, emergence speed, emergence capacity, number of normal seedlings, and number of dead seeds were determined. The results were compared with the pre-storage values to assess the effects of the six-month storage period on seed viability and early seedling development (ISTA, 2025).

Germination performance before storage after storage + transportation

To determine the effects of transportation following storage on seed performance, seeds stored for approximately six months at +5 °C and 60% relative humidity were subsequently subjected to a 16-h transportation period. Following transportation, seed viability performance was evaluated in accordance with ISTA rules. Standard germination tests were conducted to determine germination speed, germination capacity, emergence speed, emergence capacity, number of normal seedlings, and number of dead seeds. The resulting data were compared with those obtained before and after storage to determine the sequential effects of storage and subsequent transportation on seed viability and early seedling development (ISTA, 2025).

Statistical Analysis

The experiment data were analyzed using analysis of variance (ANOVA) in JMP statistical software. For factors and interactions found to be statistically significant by ANOVA, mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) multiple comparison test available in JMP (JMP, 2023). Statistical differences were evaluated at the 5% significance level ($p < 0.05$), and differences among means were indicated by letter groupings.

RESULTS AND DISCUSSION

Germination Speed

The significant effects ($p < 0.01$) of coating, storage, and cultivar, as well as their two-way and three-way interactions, on germination speed demonstrated that early germination performance in sugar beet was jointly influenced by genotype, seed-processing technology, and storage conditions (Table 1). Across all treatments, mean germination speed decreased from 85.67% in uncoated seeds to 69.92% in coated seeds, corresponding to a pronounced reduction of 18.38% due to coating (Table 2). This reduction may reflect changes in water and gas exchange caused by the coating layer, slower imbibition dynamics, and restricted leaching of germination-inhibiting compounds from the pericarp. Duan and Burris (1997) reported that polymer film coating induced genotype-dependent responses in sugar beet and could significantly reduce germination in sensitive seed lots, while Kulan and Kaya (2016) found

that uncoated seeds could exhibit higher germination and emergence performance under laboratory conditions. Similarly, Podlaski et al. (2019) demonstrated that pellet porosity, mechanical strength, water resistance, and chemical properties could influence germination behavior. Therefore, the technological advantages provided by seed coating, particularly with respect to early germination, should be evaluated by considering both the physical properties of the coating material and its compatibility with the genotype.

The marked differences among cultivars in their responses to coating further support this interpretation. The reduction in germination speed after coating reached 36.36% in Balboa, whereas it was limited to only 5.53% in Terranova and 9.92% in Gregoria, indicating that the cultivar × coating interaction was also biologically meaningful (Table 2). Mirzaei and Hemayati (2022) reported that germination characteristics in sugar beet could be significantly influenced by genotype and genotype × environment interactions, while Podlaski and Chomontowski (2020) demonstrated that seeds with similar final germination levels could nevertheless differ in vigor and early germination performance. In the present study, Terranova and Gregoria maintained relatively higher germination speed after coating, whereas Balboa exhibited a markedly more sensitive response, demonstrating that coating technologies do not induce identical physiological responses across all cultivars. These findings indicate that, in commercial seed-coating practices, not only the coating formulation but also cultivar × coating compatibility should be considered as an important criterion for optimization.

Table 1. Mean squares from the analysis of variance for germination traits of sugar beet cultivars under different coating and storage stages.

Source of Variation	DF	Germination Speed	Germination Percentage	Emergence Speed
Total	119			
Coating	1	7441,875**	8350,008**	23046,408**
Storage	2	739,733**	856,075**	66,659**
Coating × Storage Int.	2	27,300**	540,508**	28,059**
Cultivar	4	768,146**	583,179**	42,063**
Cultivar × Coating Int.	4	687,146**	317,404**	76,513**
Cultivar × Storage Int.	8	148,577**	41,367**	78,513**
Cultivar × Coating × Storage Int.	8	72,790**	29,592**	66,725**
Error	90	2,819	1,297	8,564
Source of Variation	**DF**	**Emergence Percentage**	**Number of Normal Seedlings**	**Number of Dead Seeds**
Total	119			
Coating	1	12120,300**	23,408**	21,675**
Storage	2	119,634**	4,975**	4,658**
Coating × Storage Int.	2	3,100*	0,808	0,775
Cultivar	4	300,729**	323,175**	316,783**
Cultivar × Coating Int.	4	137,154**	1,908	2,300
Cultivar × Storage Int.	8	30,123**	7,694**	7,596**
Cultivar × Coating × Storage Int.	8	21,985**	2,215*	2,088*
Error	90	0,961	0,964	0,947

*: $p<0.05$; **: $p<0.01$

Storage markedly affected germination speed, with the overall mean decreasing from 82.13% before storage to 73.53% after storage, corresponding to a reduction of 10.47%. This reduction was 8.80% in uncoated seeds and reached 12.46% in coated seeds, suggesting that coated seeds may be more sensitive to physiological changes occurring during storage (Table 2). The effects of seed aging and storage conditions on germination performance in sugar beet have previously been reported by Śliwińska (2003) and Gürel (2020), whereas appropriate seed-processing and priming treatments have been shown to mitigate performance losses during storage and under low-temperature conditions (Capron et al., 2000; Tohidloo et al., 2015; Chomontowski et al., 2020). In the three-way interaction, germination speed

ranged widely from 53.25 to 97.00%. The lowest value was observed in coated Balboa seeds after storage, whereas the highest values were recorded for uncoated Terranova seeds before storage and uncoated Preziosa seeds after transportation. This wide variation indicates that germination speed was determined primarily by the cultivar × coating × storage/transportation combination rather than by any single factor. These results suggest that cultivar-specific optimization of coating technology and storage conditions may provide a more effective approach for maintaining early germination performance in sugar beet seeds.

Table 2. Mean germination speed (%), germination percentage (%), and emergence speed (%) of sugar beet cultivars under different coating and storage stages, with statistical groupings.

Coating	Storage	Cultivars					Mean
		Balboa	Gregoria	Juncal	Preziosa	Terranova	
Germination Speed (%)							
Uncoated	Before	87,00^{cde}	93,00^{ab}	80,00^{fgh}	89,00^{bcd}	97,00^{a}	89,20^{a}
	After	79,00^{f-i}	80,75^{fg}	81,00^{fg}	86,00^{de}	80,00^{fgh}	81,35^{c}
	Transportation	87,75^{cde}	83,25^{ef}	83,50^{ef}	97,00^{a}	80,75^{fg}	86,45^{b}
	Mean	84,58^{b}	85,67^{b}	81,50^{c}	90,67^{a}	85,92^{b}	85,67
Coated	Before	53,50^{o}	81,00^{fg}	71,25^{kl}	78,00^{g-j}	91,50^{bc}	75,05^{d}
	After	53,25^{o}	75,50^{h-k}	63,50^{m}	58,25^{n}	78,00^{g-j}	65,70^{f}
	Transportation	54,75^{no}	75,00^{ijk}	73,25^{k}	68,00^{lm}	74,00 ^{jk}	69,00^{e}
	Mean	53,83^{f}	77,17^{d}	69,33^{e}	68,08^{e}	81,17^{c}	69,92
Mean	Before	70,25^{f}	87,00^{b}	75,63^{e}	83,50^{c}	94,25^{a}	82,13^{a}
	After	66,13^{g}	78,13^{de}	72,25^{f}	72,13^{f}	79,00^{d}	73,53^{c}
	Transportation	71,25^{f}	79,13^{d}	78,38^{de}	82,50^{c}	77,38^{de}	77,73^{b}
	Mean	69,21^{e}	81,42^{b}	75,42^{d}	79,38^{c}	83,54^{a}	77,79
Germination Percentage (%)							
Uncoated	Before	93,00^{cde}	99,00^{ab}	92,00^{de}	99,50^{a}	99,50^{a}	96,60^{a}
	After	94,00^{cd}	92,75^{de}	90,25^{ef}	94,75^{cd}	99,75^{a}	94,30^{b}
	Transportation	94,00^{cd}	92,00^{de}	95,00^{cd}	99,00^{ab}	99,75^{a}	95,95^{a}
	Mean	93,67^{cd}	94,58^{c}	92,42^{d}	97,75^{b}	99,67^{a}	95,62
Coated	Before	78,00^{jk}	92,25^{de}	90,75^{e}	85,00^{gh}	96,00^{bc}	88,40^{c}
	After	60,25^{n}	82,25^{hi}	70,50^{l}	65,25^{m}	87,25^{fg}	73,10^{e}
	Transportation	64,25^{m}	80,00^{ij}	76,25^{k}	75,00^{k}	81,00^{ij}	75,30^{d}
	Mean	67,50^{i}	84,83^{f}	79,17^{g}	75,08^{h}	88,08^{e}	78,93
Mean	Before	85,50^{f}	95,63^{b}	91,38^{d}	92,25^{cd}	97,75^{a}	92,50^{a}
	After	77,13^{h}	87,50^{e}	80,38^{g}	80,00^{g}	93,50^{c}	83,70^{c}
	Transportation	79,13^{g}	86,00^{ef}	85,63^{ef}	87,00^{ef}	90,38^{d}	85,63^{b}
	Mean	80,58^{d}	89,71^{b}	85,79^{c}	86,42^{c}	93,88^{a}	87,28
Emergence Speed (%)							
Uncoated	Before	93,75^{abc}	97,00^{a}	96,00^{ab}	98,00^{a}	97,00^{a}	96,35^{a}
	After	93,75^{abc}	95,00^{abc}	87,00^{c}	95,00^{abc}	98,00^{a}	93,75^{ab}
	Transportation	92,00^{abc}	90,00^{abc}	88,00^{bc}	93,75^{abc}	98,00^{a}	92,35^{b}
	Mean	93,17^{bc}	94,00^{abc}	90,33^{c}	95,58^{ab}	97,67^{a}	94,15
Coated	Before	65,00^{e-h}	60,75^{gh}	73,75^{d}	68,75^{d-g}	65,25^{e-h}	66,70^{c}
	After	65,50^{e-h}	70,00^{def}	64,00^{fgh}	63,00^{fgh}	72,75^{de}	67,05^{c}
	Transportation	63,25^{fgh}	74,25^{d}	65,25^{e-h}	64,75^{e-h}	60,25^{h}	65,55^{c}
	Mean	64,58^{d}	68,33^{d}	67,67^{d}	65,50^{d}	66,08^{d}	66,43
Mean	Before	79,38^{b-e}	78,88^{b-e}	84,88^{a}	83,38^{ab}	81,13^{a-d}	81,53^{a}
	After	79,63^{b-e}	82,50^{abc}	75,50^{e}	79,00^{b-e}	85,38^{a}	80,40^{ab}
	Transportation	77,63^{cde}	82,13^{abc}	76,63^{de}	79,25^{b-e}	79,13^{b-e}	78,95^{b}
	Mean	78,88^{b}	81,17^{ab}	79,00^{b}	80,54^{ab}	81,88^{a}	80,29

[1]Means followed by the same letter are not significantly different.

Germination Percentage

The significant effects of coating, storage, and cultivar, as well as their two-way and three-way interactions, on germination percentage demonstrated that seed performance was determined by the combined effects of genotype, seed processing, and storage conditions rather than by a single factor (Table 1). The decrease in germination percentage from 95.62% in uncoated seeds to 78.93% in coated seeds, a reduction of approximately 17.45%, may be associated with the coating material's physical effects on imbibition and gas exchange (Table 2). In addition to restricting water and oxygen uptake, the coating layer may delay the leaching of water-soluble inhibitors present in the pericarp, thereby limiting germination, particularly in sensitive seeds. Duan and Burris (1997) reported that polymer film coating could reduce germination in sugar beet depending on genotype and seed lot, while Kulan and Kaya (2016) found that uncoated seeds exhibited higher germination performance under laboratory conditions. Podlaski et al. (2019) further demonstrated that pellet porosity, mechanical strength, water resistance, and chemical composition were important determinants of germination behavior. Conversely, reports that treatments such as polishing and washing can improve germination by reducing ABA and other inhibitory compounds in the pericarp (Ignatz et al., 2019) suggest that the effect of coating depends not merely on the presence of the coating itself but also on the physical and physiological interactions among the seed, pericarp, and coating material.

The response to coating varied considerably among cultivars, highlighting the critical role of genotypic differences in coating performance. The reduction in germination percentage due to coating reached 27.94% in Balboa and 23.19% in Preziosa, whereas the corresponding losses were limited to 10.31% in Gregoria and 11.63% in Terranova. Across all treatments, Terranova had the highest germination percentage at 93.88%, whereas Balboa had the lowest at 80.58%. Among coated seeds, Terranova maintained a relatively high germination percentage of 88.08%, while that of Balboa decreased to 67.50% (Table 2). These differences demonstrate that the same coating technology does not produce equivalent physiological responses across genotypes. The findings of Mirzaei and Hemayati (2022), who reported significant effects of genotype and genotype × environment interactions on germination characteristics in sugar beet, support this interpretation. Similarly, differences in early germination behavior between high- and low-vigor seeds despite similar final germination levels emphasize the importance of initial seed quality and genotypic characteristics in determining post-coating performance (Chomontowski et al., 2020). Therefore, the substantial losses observed particularly in Balboa and Preziosa indicate the importance of considering genotype-specific coating formulations and cultivar × coating compatibility rather than adopting a uniform coating approach in commercial seed-processing systems.

Storage further accentuated the effect of coating on germination percentage. Overall germination decreased from 92.50% before storage to 83.70% after storage; more importantly, this reduction was only 2.38% in uncoated seeds but reached 17.31% in coated seeds (Table 2). Although germination partially recovered after transportation, it did not return to the pre-storage level. Because controlled aging can reduce germination performance in sugar beet (Śliwińska, 2003) and storage performance depends on factors such as initial seed quality, temperature, and relative humidity (Gürel, 2020), these results indicate that the effects of coating and storage cannot be considered independently. In contrast, appropriate seed-processing and priming treatments have been reported to mitigate performance losses during storage and under low-temperature conditions (Capron et al., 2000; Tohidloo et al., 2015; Chomontowski et al., 2020). Therefore, maintaining germination percentage in sugar beet depends not only on high initial seed quality but also on cultivar × coating × storage/transportation compatibility. Accordingly, cultivar-specific optimization of coating physical properties and storage stability appears critical for maintaining commercial seed quality until sowing.

Emergence Speed

The significant effects of coating, storage, and cultivar on emergence speed, together with significant cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions, demonstrated that early seedling performance was determined by the combined effects of genotype and seed-processing conditions (Table 1). In particular, coating reduced emergence speed from 94.15% in uncoated seeds to 66.43% in coated seeds, a reduction of approximately 29.44% and the most pronounced effect among the factors examined (Table 2). This reduction may be associated with restricted imbibition and oxygen diffusion caused by the coating material, increased physical resistance to radicle emergence, and delayed

leaching of germination inhibitors from the pericarp. Duan and Burris (1997) reported that film coating could delay germination in certain sugar beet genotypes, while Podlaski et al. (2019) demonstrated that pellet porosity, breaking force, water resistance, and water potential could determine germination and early seedling performance. Similarly, Kulan and Kaya (2016) found that uncoated sugar beet seeds could exhibit higher germination and emergence performance under laboratory conditions. These results indicate that, despite the technological advantages of coating, coating materials should be optimized to avoid restricting early seedling development.

The effect of coating on emergence speed varied among genotypes, demonstrating the biological significance of the cultivar × coating interaction. In uncoated seeds, emergence speed ranged from 90.33 to 97.67%, showing clear differences among cultivars, whereas in coated seeds the values narrowed to 64.58–68.33%, with all cultivars belonging to the same statistical group. The reduction associated with coating was limited to 25.09% in Juncal but reached 32.34% in Terranova, 31.47% in Preziosa, and 30.69% in Balboa (Table 2). These findings are noteworthy because coating not only reduced overall emergence speed but also largely suppressed the genotypic differences observed among uncoated seeds. Mirzaei and Hemayati (2022) reported that genotype and genotype × environment interactions significantly influenced germination characteristics in sugar beet, supporting a strong genotypic component in early seedling performance. Therefore, coating should not be assumed to produce similar physiological responses across all genotypes; instead, the structure and application characteristics of the coating material should be evaluated alongside the physiological characteristics of each cultivar.

Storage had a more limited effect on emergence speed than coating. The overall mean decreased from 81.53% before storage to 80.40% after storage and to 78.95% after transportation. Uncoated seeds largely maintained their pre-storage emergence speed of 96.35%, with values of 93.75% after storage and 92.35% after transportation, whereas coated seeds remained at approximately 65–67% throughout all stages. This indicates that coating, rather than storage, was the principal limitation on emergence speed. Nevertheless, within the cultivar × coating × storage interaction, emergence speed in uncoated Terranova seeds was 98.00% after transportation but fell to 60.25% in coated seeds at the same stage, showing that storage and transportation effects cannot be evaluated independently of coating and genotype (Table 2). Considering the physiological changes associated with storage and aging reported by Śliwińska (2003) and Gürel (2020), these findings indicate that the physical properties of coating materials, genotypic sensitivity, and storage/transportation conditions should be jointly optimized to maintain high emergence performance in sugar beet.

Emergence Percentage

The significant effects of coating, storage, and cultivar on emergence percentage, along with significant two-way and three-way interactions among these factors, showed that early seedling establishment in sugar beet was determined by the combined effects of genotype, seed-processing technology, and storage conditions (Table 1). Coating reduced emergence percentage from 96.22% in uncoated seeds to 76.12% in coated seeds, corresponding to a reduction of approximately 20.89% (Table 3). This pronounced reduction may be associated with restricted water uptake and oxygen diffusion caused by the coating material, increased mechanical resistance to radicle emergence, and delayed leaching of water-soluble inhibitors from the pericarp. Duan and Burris (1997) reported that polymer film coating could restrict germination, particularly in sensitive sugar beet genotypes, while Podlaski et al. (2019) demonstrated that pellet porosity, breaking force, water resistance, and water potential were important determinants of germination and early seedling performance. Similarly, Kulan and Kaya (2016) found that uncoated sugar beet seeds could exhibit higher germination and emergence performance than coated seeds. These findings indicate that, despite the commercial and agronomic advantages of coating, coating materials should be optimized to avoid restricting water–gas exchange and early seedling development.

The marked variation among cultivars in their response to coating demonstrated the importance of genotypic characteristics in maintaining emergence percentage. The coating-related reduction in emergence percentage reached 26.40% in Balboa and 25.26% in Preziosa, whereas the reduction was more limited in Terranova at 14.22%. Furthermore, Terranova maintained the highest emergence percentage in both uncoated (99.00%) and coated (84.92%) seeds, whereas Balboa exhibited the lowest performance under coated conditions at 70.17%. These differences demonstrate that the same coating treatment does not produce equivalent physiological responses across genotypes and that cultivar ×

coating compatibility is an important component of commercial seed quality (Table 3). Mirzaei and Hemayati (2022) reported that genotype and genotype × environment interactions significantly affected germination characteristics in sugar beet, while Podlaski and Chomontowski (2020) emphasized the importance of early germination and emergence performance for identifying differences in seed vigor. Therefore, the relatively high emergence percentage maintained by Terranova after coating, compared with the more pronounced losses observed in Balboa and Preziosa, indicates that coating formulations and application characteristics should be evaluated on a genotype-specific basis.

Table 3. Mean emergence percentage (%), number of normal seedlings, and number of dead seeds of sugar beet cultivars under different coating and storage stages, with statistical groupings.

Coating	Storage	Cultivars					Mean
		Balboa	Gregoria	Juncal	Preziosa	Terranova	
Emergence Percentage (%)							
Uncoated	Before	96,00^{bc}	98,75^{a}	98,00^{ab}	99,00^{a}	99,00^{a}	98,15^{a}
	After	95,00^{cd}	96,00^{bc}	93,25^{de}	97,25^{abc}	99,00^{a}	96,10^{b}
	Transportation	95,00^{cd}	91,00^{ef}	90,25^{fg}	96,75^{abc}	99,00^{a}	94,40^{c}
	Mean	95,33^{c}	95,25^{c}	93,83^{d}	97,67^{b}	99,00^{a}	96,22
Coated	Before	69,75^{mn}	79,00^{j}	80,75^{ij}	75,00^{k}	85,25^{h}	77,95^{d}
	After	71,75^{lm}	75,25^{k}	71,75^{lm}	71,00^{lmn}	87,75^{gh}	75,50^{e}
	Transportation	69,00^{n}	79,75^{ij}	71,00^{lmn}	73,00^{kl}	81,75^{i}	74,90^{e}
	Mean	70,17^{i}	78,00^{f}	74,50^{g}	73,00^{h}	84,92^{e}	76,12
Mean	Before	82,88^{fg}	88,88^{b}	89,38^{b}	87,00^{c}	92,13^{a}	88,05^{a}
	After	83,38^{efg}	85,63^{cd}	82,50^{fg}	84,13^{def}	93,38^{a}	85,80^{b}
	Transportation	82,00^{gh}	85,38^{cd}	80,63^{h}	84,88^{de}	90,38^{b}	84,65^{c}
	Mean	82,75^{e}	86,63^{b}	84,17^{d}	85,33^{c}	91,96^{a}	86,17
Number of Normal Seedlings							
Uncoated	Before	86,75^{f}	94,75^{d}	94,75^{d}	97,00^{a-d}	99,00^{a}	94,45
	After	89,75^{e}	97,00^{a-d}	96,00^{cd}	97,25^{a-d}	95,75^{cd}	95,15
	Transportation	90,25^{e}	97,00^{a-d}	94,75^{d}	98,00^{abc}	96,75^{a-d}	95,35
	Mean	88,92	96,25	95,17	97,42	97,17	94,98
Coated	Before	88,00^{ef}	96,75^{a-d}	96,75^{a-d}	97,75^{abc}	99,00^{a}	95,65
	After	90,00^{e}	96,25^{bcd}	97,00^{a-d}	97,75^{abc}	98,00^{abc}	95,80
	Transportation	89,25^{ef}	98,00^{abc}	96,75^{a-d}	98,75^{ab}	98,00^{abc}	96,15
	Mean	89,08	97,00	96,83	98,08	98,33	95,87
Mean	Before	87,38^{f}	95,75^{d}	95,75^{d}	97,38^{a-d}	99,00^{a}	95,05^{b}
	After	89,88^{e}	96,63^{cd}	96,50^{cd}	97,50^{abc}	96,88^{bcd}	95,48^{ab}
	Transportation	89,75^{e}	97,50^{abc}	95,75^{d}	98,38^{ab}	97,38^{a-d}	95,75^{a}
	Mean	89,00^{c}	96,63^{b}	96,00^{b}	97,75^{a}	97,75^{a}	95,43
Number of Dead Seeds							
Uncoated	Before	13,00^{a}	5,25^{c}	5,25^{c}	3,00^{c-f}	1,00^{f}	5,50
	After	10,00^{b}	3,00^{c-f}	4,00^{cd}	2,75^{c-f}	4,25^{cd}	4,80
	Transportation	9,75^{b}	3,00^{c-f}	5,25^{c}	2,00^{def}	3,25^{c-f}	4,65
	Mean	10,92	3,75	4,83	2,58	2,83	4,98
Coated	Before	12,00^{ab}	3,25^{c-f}	3,25^{c-f}	2,25^{def}	1,00^{f}	4,35
	After	10,00^{b}	3,75^{cde}	3,00^{c-f}	2,25^{def}	2,00^{def}	4,20
	Transportation	10,75^{ab}	2,00^{def}	3,25^{c-f}	1,25^{ef}	2,00^{def}	3,85
	Mean	10,92	3,00	3,17	1,92	1,67	4,13
Mean	Before	12,50^{a}	4,25^{c}	4,25^{c}	2,63^{c-f}	1,00^{f}	4,93^{a}
	After	10,00^{b}	3,38^{cd}	3,50^{cd}	2,50^{def}	3,13^{cde}	4,50^{ab}
	Transportation	10,25^{b}	2,50^{def}	4,25^{c}	1,63^{ef}	2,63^{c-f}	4,25^{b}
	Mean	10,92^{a}	3,38^{b}	4,00^{b}	2,25^{c}	2,25^{c}	4,56

[1]Means followed by the same letter are not significantly different.

Storage and transportation resulted in a more limited but gradual reduction in emergence percentage compared with the effect of coating. The overall mean decreased from 88.05% before storage to 85.80% after storage and further to 84.65% after transportation. In uncoated seeds, emergence decreased from 98.15% before storage to 94.40% after transportation, whereas in coated seeds it declined from 77.95% to 74.90% over the same period, with coated seeds consistently performing worse at all stages (Table 3). This trend is consistent with the physiological deterioration associated with storage and aging reported by Śliwińska (2003) and Gürel (2020). However, the significant cultivar × storage interaction indicated that genotypes responded differently to storage and transportation conditions. In particular, Terranova largely maintained its performance, whereas Juncal's emergence percentage decreased from 89.38% before storage to 80.63% after transportation. These findings demonstrate that maintaining a high emergence percentage in sugar beet depends not only on appropriate storage conditions but also on the combined management of coating material properties and genotypic sensitivity. In particular, cultivar × coating × storage/transportation compatibility should be considered a key optimization criterion for maintaining commercial seed quality.

Number of Normal Seedlings

Although cultivar, coating, and storage significantly affected the number of normal seedlings, the coating × storage and cultivar × coating interactions were not significant, indicating that genotypic differences and cultivar-specific responses to storage primarily determined this trait (Table 1). Coating increased the number of normal seedlings from 94.98 in uncoated seeds to 95.87 in coated seeds, corresponding to a limited increase of approximately 0.94%. This result indicates that coating did not have a pronounced adverse effect on the ability to produce normal seedlings and that initial seedling quality could be maintained under appropriate coating conditions (Table 3). Tohidloo et al. (2015) reported that appropriate seed-processing treatments could support normal seedling development in sugar beet and that treated seeds could maintain their performance after six months of storage, while Ignatz et al. (2019) demonstrated that reducing ABA, ions, and other inhibitory compounds in the pericarp could improve normal seedling development. Similarly, Capron et al. (2000) and Chomontowski et al. (2020) reported that appropriate priming treatments could promote germination and early seedling development, particularly in low-vigor seeds. Therefore, the effect of coating on normal seedling development should be evaluated not merely in terms of the presence or absence of a coating but also in relation to the initial physiological quality of the seeds and the characteristics of the seed-processing technology applied.

The pronounced differences among cultivars demonstrated the importance of genotypic effects on the ability to produce normal seedlings. Averaged across coating and storage stages, Preziosa and Terranova had the highest number of normal seedlings (97.75), followed by Gregoria and Juncal (96.63 and 96.00, respectively), whereas Balboa was clearly distinguished from the other cultivars with the lowest value (89.00). Accordingly, the number of normal seedlings in Preziosa and Terranova was approximately 9.83% higher than that in Balboa. In particular, coated Preziosa seeds exhibited high and stable performance, producing 97.75 normal seedlings before storage, 97.75 after storage, and 98.75 after transportation, indicating that this cultivar maintained a high degree of stability during seed processing, storage, and transportation. In contrast, the lower number of normal seedlings observed in Balboa across different coating and storage combinations suggests that initial seed vigor and genotypic characteristics may play a decisive role in normal seedling development (Table 3). The findings of Mirzaei and Hemayati (2022), who reported that genotypic differences significantly influenced early developmental characteristics in sugar beet, further support the present results. These findings indicate that commercial seed quality assessment should consider not only the overall effect of coating but also individual cultivars' ability to produce normal seedlings and maintain stable performance across treatments.

Regarding storage, the number of normal seedlings was 95.05 before storage, 95.48 after storage, and 95.75 after transportation, indicating that the capacity to produce normal seedlings was largely maintained throughout approximately six months of storage and the subsequent transportation period. However, significant cultivar × storage and cultivar × coating × storage interactions showed that this overall stability was not maintained equally across all genotypes. In the three-way interaction, the highest number of normal seedlings (99.00) was recorded for both uncoated and coated Terranova seeds before storage, whereas the lowest value (86.75) was observed in uncoated Balboa seeds before storage. Furthermore, Preziosa and Terranova largely maintained their high capacity to produce normal seedlings

across different treatment combinations (Table 3). When considered together with the differences related to genotype, initial physiological quality, and storage stability reported by Śliwińska (2003), Tohidloo et al. (2015), and Podlaski and Chomontowski (2020), the present results indicate that coating and storage conditions should be evaluated in conjunction with genotypic seed vigor to maintain a high capacity for normal seedling development in sugar beet. Moreover, cultivar stability during storage and transportation should be considered an important selection criterion for commercial seed quality.

Number of Dead Seeds

Although cultivar, coating, and storage significantly affected the number of dead seeds, the coating × storage and cultivar × coating interactions were not significant, indicating that genotypic differences and cultivar-specific responses to storage largely determined this trait (Table 1). The decrease in dead seeds from 4.98 in uncoated seeds to 4.13 in coated seeds, a reduction of approximately 17.07%, suggests that coating did not adversely affect seed viability and, under appropriate conditions, may help maintain it (Table 3). Tohidloo et al. (2015) reported that appropriate seed-processing treatments could contribute to maintaining germination performance and normal seedling development in sugar beet, while Ignatz et al. (2019) demonstrated that reducing ABA, ions, and other inhibitory compounds present in the pericarp could improve germination performance. Similarly, Capron et al. (2000) and Chomontowski et al. (2020) reported that appropriate priming treatments could support seed viability and early developmental performance, particularly in low-vigor seeds. These findings indicate that the effect of coating on the number of dead seeds should be evaluated not only in terms of the coating treatment itself but also in relation to initial seed quality, coating material characteristics, and the seed's physiological response following processing.

The wide variation among cultivars clearly demonstrated the importance of genotypic effects in determining the number of dead seeds. Averaged across coating treatments and storage stages, Balboa had the highest number of dead seeds at 10.92, whereas Juncal and Gregoria showed intermediate values of 4.00 and 3.38, respectively, and Preziosa and Terranova had the lowest values at 2.25. Thus, the number of dead seeds in Balboa was approximately 4.85 times higher than that in Preziosa and Terranova. While Balboa maintained a relatively high number of dead seeds under both uncoated and coated conditions, the number decreased to as low as 1.25 in coated Preziosa seeds after transportation, indicating a strong genotype-dependent response to coating and processing conditions (Table 3). The findings of Mirzaei and Hemayati (2022), who reported significant effects of genotype and genotype × environment interactions on germination characteristics in sugar beet, and those of Podlaski and Chomontowski (2020), who emphasized initial seed vigor as a major determinant of subsequent performance, support the present results. Therefore, reducing the number of dead seeds in commercial sugar beet seed lots requires considering not only coating technology but also genotypic viability potential and initial seed quality as key selection criteria.

For storage and transportation, the number of dead seeds decreased from 4.93 before storage to 4.50 after storage and further to 4.25 after transportation, indicating that approximately six months of storage followed by transportation did not increase seed mortality under the conditions of the present experiment. However, the significant cultivar × storage and cultivar × coating × storage interactions demonstrated that this overall trend was not consistent across all genotypes. Balboa maintained a relatively high number of dead seeds at all stages, whereas Preziosa decreased to 1.63 after transportation. In the three-way interaction, values ranged from 1.00 to 13.00, with the highest value observed in the uncoated Balboa × before-storage combination and the lowest values recorded in both uncoated and coated Terranova × before-storage combinations (Table 3). Reports by Śliwińska (2003), Gürel (2020), and Tohidloo et al. (2015) indicate that storage performance depends on initial physiological quality, genotype, and storage conditions, supporting this variation. Overall, maintaining a low number of dead seeds and preserving seed viability during storage and transportation in sugar beet requires considering initial seed quality and the storage stability of individual cultivars, while coating and storage protocols should be optimized according to genotype-specific responses.

CONCLUSION

This study showed that the effects of seed coating, storage, and transportation on germination and early seedling performance in sugar beet varied considerably by genotype and trait. Coating reduced germination speed from 85.67% to 69.92%, final germination percentage from 95.62% to 78.93%,

emergence speed from 94.15% to 66.43%, and final emergence percentage from 96.22% to 76.12%, indicating a pronounced limitation of germination and emergence performance. In contrast, coating increased the number of normal seedlings from 94.98 to 95.87 and reduced the number of dead seeds from 4.98 to 4.13. Significant differences were also observed among cultivars. Terranova showed high final germination and final emergence percentages, whereas Preziosa and Terranova had high numbers of normal seedlings and low numbers of dead seeds. In contrast, Balboa generally showed lower germination performance and seed viability.

Although storage and transportation affected the traits differently, the larger reductions in germination-related traits in coated seeds, along with significant cultivar × coating × storage/transportation interactions, showed that these processes should not be evaluated independently of genotype. Overall, the results indicate that commercial sugar beet seed production should prioritize cultivar × coating compatibility rather than relying on a uniform coating strategy. Furthermore, coating materials should be optimized to minimize restrictions on water uptake and gas exchange, while storage and transportation conditions should be managed according to genotype-specific sensitivity. Such an integrated approach is critical for maintaining high germination performance and seed quality until sowing.

ACKNOWLEDGMENTS

This study was supported by the Scientific Research Projects Coordination Unit of Selçuk University under Project No. 25201027. This study was prepared as part of the M.Sc. thesis conducted by Hamza DOGAN at the Department of Field Crops, Graduate School of Natural and Applied Sciences, Selçuk University.

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EFFECTS OF COATING, STORAGE AND TRANSPORTATION ON EARLY SEEDLING GROWTH IN SUGAR BEET CULTIVARS

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ABSTRACT
Rapid, balanced seedling development is critical for uniform crop establishment and maintaining yield potential in sugar beet. This study aimed to determine the effects of seed coating, storage, and transportation processes on early seedling growth traits in different sugar beet cultivars. Uncoated and coated seeds of Balboa, Gregoria, Juncal, Preziosa, and Terranova were evaluated before storage, after about six months of storage at 5 °C and 60% relative humidity, and after a subsequent 16-h transportation period. Seedling length, root length, vegetative fresh and dry weight, and root fresh and dry weight were assessed. The results demonstrated that seed coating, storage/transportation stage, cultivar, and their interactions markedly influenced early seedling development, with responses varying among genotypes. Mean seedling length increased from 5.75 cm in uncoated seeds to 5.92 cm in coated seeds, while the highest overall seedling length was recorded after transportation at 6.03 cm. In contrast, root length decreased from 9.03 cm in uncoated seeds to 8.15 cm following coating. Vegetative fresh weight increased from 0.317 to 0.331 g, whereas vegetative dry weight increased from 0.019 to 0.021 g. Cultivar-specific responses to coating were pronounced; Terranova and Juncal showed particularly positive responses in vegetative dry matter accumulation. Conversely, root dry weight declined from 0.021 g in uncoated seeds to 0.018 g in coated seeds. Overall, seed coating may promote shoot elongation and vegetative biomass accumulation while simultaneously restricting root development, and the magnitude and direction of these responses depend strongly on cultivar and post-coating storage conditions. Therefore, seed coating and storage protocols should be optimized on a genotype-specific basis to maintain vigorous and balanced early seedling development in commercial sugar beet seed production.
Keywords: Root Growth, Seed Coating, Seedling Development, Storage, Transportation.

INTRODUCTION
Sugar beet (*Beta vulgaris* L.) is a principal raw material of the sugar industry and a strategically important industrial crop in many countries because of its high economic value. Achieving high yield and quality in sugar beet production depends on the rapid establishment of a uniform crop stand after sowing and the maintenance of an optimum plant population per unit area (Kockelmann and Meyer, 2006; Kockelmann et al., 2010). Because irregular emergence and seedling losses occurring during the early stages of plant development cannot be adequately compensated for at later growth stages, the ability of seeds to produce vigorous and uniform seedlings is critical for successful crop establishment (Kulan and Kaya, 2016; Podlaski and Chomontowski, 2020). Therefore, seed quality assessment should not rely solely on final germination percentage but should also consider early developmental traits such as seedling and root growth, biomass accumulation, and the capacity to produce normal seedlings. Indeed, high seed vigor has been associated with rapid and uniform emergence, vigorous seedling development, and greater tolerance to environmental stress conditions (Finch-Savage and Bassel, 2016; Ma et al., 2022).
Early seedling performance depends on the combined effects of numerous factors, including genetic background, environmental conditions during seed development and maturation, harvest timing, initial physiological quality, seed processing treatments, and storage conditions (Finch-Savage and Bassel, 2016; Leprince et al., 2016).

Environmental conditions experienced during seed development and maturation may affect not only germination capacity but also seed vigor and subsequent seedling development (Mirzaei and Hemayati, 2022). In sugar beet, harvest maturity and seed moisture content are important determinants of physiological seed quality and storability, whereas unfavorable conditions may accelerate losses in viability and vigor (Śliwińska et al., 1999; Śliwińska, 2003). In particular, physiological aging during storage may reduce seed vigor before a pronounced decline in germination becomes apparent, making early seedling growth traits valuable indicators of changes in seed quality (Walters et al., 2005; Solberg et al., 2020; Zinsmeister et al., 2020). Accordingly, traits such as seedling length, root length, fresh and dry biomass accumulation, and normal seedling formation represent important physiological criteria for assessing the effects of storage and other post-processing operations on seed performance.

A substantial proportion of commercial seeds used in modern sugar beet production undergo coating or pelleting to improve their physical characteristics for precision sowing and to facilitate the application of various active ingredients to the seed surface. Seed-coating technologies give irregularly shaped sugar beet seeds more standardized size and shape, facilitating precision sowing while enabling controlled, uniform delivery of protective compounds, nutrients, and biostimulants (Rocha et al., 2019; Afzal et al., 2020). However, the effects of coating on early seedling development may vary depending on the physical and physicochemical properties of the filler and binder materials used. Excessive mechanical resistance of the coating layer or insufficient porosity may restrict water and oxygen uptake, thereby adversely affecting radicle emergence and subsequent root and shoot development (Afzal et al., 2020; Ma et al., 2022). Considering that the structural characteristics of the pericarp and the presence of germination-inhibiting compounds, including phenolic compounds, abscisic acid, and various ions, may also influence germination in sugar beet seeds, interactions between the coating material and the seed may be particularly important in determining early seedling development (Duan and Burris, 1997; Ignatz et al., 2019).

The ability of coated seeds to maintain physiological quality until sowing depends not only on the coating treatment but also on the conditions encountered during storage and transportation. Temperature, relative humidity, and seed moisture content are among the major factors determining the rate of seed aging during storage. High temperature and humidity accelerate physiological deterioration, whereas appropriate storage conditions maintain seed viability and vigor for longer periods (Walters et al., 2005; Gürel, 2020; Solberg et al., 2020). In coated seeds, the coating material's physical integrity must also be maintained. Binder and filler materials used in coating formulations, together with drying conditions, may affect the mechanical strength, porosity, water permeability, and disintegration behavior of the pellet, and changes in these properties may subsequently influence seedling development (Afzal et al., 2020; Paravar et al., 2023; Köhl et al., 2024). Furthermore, vibration, friction, and other mechanical forces during transportation may cause abrasion, cracking, or fragmentation of the coating surface, potentially altering seed physiological performance at sowing after storage and transportation. Evidence that differences in pellet breaking strength, abrasion resistance, water resistance, and porosity can influence sugar beet seed performance, particularly under suboptimal moisture conditions, further highlights the importance of evaluating coating, storage, and transportation processes in an integrated manner (Podlaski et al., 2019).

Previous studies on sugar beet have separately investigated the effects of coating and pelleting characteristics, priming, polishing and washing treatments, and storage conditions on seed germination, emergence, and seedling development (Duan and Burris, 1997; Capron et al., 2000; Marcinek et al., 2011; Ignatz et al., 2019; Podlaski et al., 2019; Chomontowski et al., 2020; Gürel, 2020). However, studies simultaneously evaluating the sequential effects of seed coating, storage, and transportation on early seedling growth traits across different sugar beet cultivars remain limited. Moreover, because genotypic differences may result in cultivar-specific physiological responses to these processes, coating and storage/transportation treatments should be evaluated at the cultivar level. Therefore, the present study aimed to compare the early seedling growth performance of uncoated and coated seeds of different sugar beet cultivars before storage, after storage, and after storage plus transportation by evaluating seedling length, root length, vegetative fresh and dry weight, and root fresh and dry weight. The study further aimed to elucidate cultivar × coating × storage/transportation interactions affecting early seedling development and to provide a scientific basis for storage and logistical practices designed to maintain the physiological quality of commercial sugar beet seeds until sowing.

MATERIALS AND METHODS

Plant Material

This study was conducted during 2024–2025 in the laboratories of the Ankara Seed Registration and Certification Directorate to determine the physiological quality and early seedling growth performance of uncoated and coated sugar beet (*Beta vulgaris* L.) seeds before storage, after storage, and after storage plus transportation. Seeds of five sugar beet cultivars, Balboa, Gregoria, Juncal, Preziosa, and Terranova, were used as plant material. To allow direct comparison of coating treatments, seeds from the same seed lot of each cultivar were divided into two groups: coated and uncoated. Seed coating was performed by ABEL Ziraat A.Ş. at a coating ratio of 1:1 (w/w), corresponding to the application of 1 kg of coating material per 1 kg of seed. The cultivars used in the study differed in their agronomic characteristics and disease tolerance. Balboa is characterized by its monogerm, root-sugar type and tolerance to *Rhizomania*; Gregoria by high resistance to *Rhizomania* and tolerance to *Cercospora* leaf spot and powdery mildew; Juncal by its monogerm, root-sugar type, *Fusarium* tolerance, and suitability for early sowing; Preziosa by high resistance to *Rhizomania* and tolerance to cyst nematode and *Cercospora* leaf spot; and Terranova by high resistance to *Rhizomania* and tolerance to *Cercospora* leaf spot and powdery mildew. Furthermore, Balboa and Juncal achieved mean root yields of 8.88 and 7.87 t ha^{-1}, respectively, in registration trials, with sugar contents of 17.10% and 15.35%, respectively. Thus, cultivars with contrasting genetic and agronomic characteristics enabled comparison of cultivar-specific responses to coating, storage, and transportation.

Methods

Seed Physiological Quality Before Storage

To determine physiological quality before storage, seeds obtained from harvested plants that had not yet been subjected to any storage or transportation process were used. Standard germination tests were conducted in accordance with the rules of the International Seed Testing Association (ISTA) to determine the initial physiological quality of the seeds. Seedling length, root length, and fresh and dry biomass accumulation were determined. These values served as baseline data for evaluating changes after storage and transportation (ISTA, 2025).

Seed Physiological Quality After Storage

To determine the effects of storage on seed physiological quality and early seedling development, seeds were stored for approximately six months at +5 °C and 60% relative humidity. Following completion of the storage period, physiological seed quality was reassessed in accordance with ISTA rules. Standard germination tests were conducted, and seedling length, root length, and fresh and dry biomass accumulation were determined. The results were compared with the pre-storage values to assess the effects of the six-month storage period on seed physiological quality and early seedling development (ISTA, 2025).

Seed Physiological Quality After Storage and Transportation

To determine the effects of post-storage transportation on seed performance, seeds stored for approximately six months at +5 °C and 60% relative humidity underwent a 16-h transportation period. Following transportation, seed physiological quality and early seedling growth performance were evaluated in accordance with ISTA rules. Seedling length, root length, and fresh and dry biomass accumulation were determined. The resulting data were compared with those obtained before and after storage to evaluate the sequential effects of storage and subsequent transportation on seed physiological quality and early seedling development (ISTA, 2025).

Statistical Analysis

Data from the study were analyzed using analysis of variance (ANOVA) in JMP statistical software. When ANOVA detected significant effects, treatment means were compared using Tukey's Honestly Significant Difference (HSD) multiple-comparison test in JMP (JMP, 2023). Statistical significance was evaluated at the 5% probability level ($p < 0.05$), and differences among means were indicated by letter groupings.

RESULTS AND DISCUSSION

Seedling Length

The significant effects of coating, storage, and cultivar on seedling length, together with the significant coating × storage, cultivar × coating, and cultivar × storage × coating interactions, indicate that early seedling development in sugar beet is jointly influenced by genotype and seed processing conditions (Table 1). Overall, coating increased seedling length from 5.75 cm in uncoated seeds to 5.92 cm in coated seeds, corresponding to an increase of approximately 2.96%. In coated seeds, seedling length increased from 5.47 cm before storage to 6.32 cm after transportation. In contrast to the adverse effects of coating previously observed for germination and emergence traits, these findings suggest that, although coating may delay initial development under certain conditions, it may subsequently promote seedling elongation (Table 2). Similarly, Chomontowski et al. (2020) reported that appropriate priming treatments could promote early plant development, while Capron et al. (2000) demonstrated that hydropriming and osmopriming could improve germination and early growth performance in sugar beet. Ignatz et al. (2019) further showed that reducing ABA and other inhibitory compounds in the pericarp could facilitate faster and more normal seedling development. Therefore, the effects of coating on seedling development should be evaluated not only for potential delays during germination but also for post-germination growth dynamics.

The direction and magnitude of seedling growth responses to coating differed among cultivars, clearly demonstrating the importance of the cultivar × coating interaction. Coating increased seedling length by 18.64% in Balboa, 7.48% in Gregoria, and 3.43% in Juncal, whereas it decreased seedling length by 9.08% in Preziosa and 2.90% in Terranova. Particularly noteworthy was Balboa, which showed one of the lowest seedling lengths under the uncoated treatment (5.31 cm) but reached 6.30 cm after coating, one of the highest values among the cultivars. In contrast, Preziosa, which exhibited the greatest seedling length under the uncoated treatment (6.28 cm), decreased to 5.71 cm following coating. These contrasting responses demonstrate that the same coating treatment may induce opposite growth responses depending on the cultivar (Table 2). The findings of Mirzaei and Hemayati (2022), who reported significant effects of genotype and genotype × environment interactions on early growth traits in sugar beet, are consistent with this genotypic differentiation. Collectively, these findings suggest that the effectiveness of coating in promoting early seedling development depends not only on coating material characteristics but also on the genotype's physiological response to the microenvironment created by the coating. Therefore, evaluate coating × genotype compatibility on a cultivar-specific basis.

Across storage stages, seedling length increased from 5.64 cm before storage to 5.84 cm after storage and 6.03 cm after transportation, representing a response that differed from the declining trend previously observed for germination and emergence traits. This increase was particularly pronounced in coated seeds, in which seedling length increased from 5.47 cm before storage to 6.32 cm after transportation, whereas uncoated seeds showed relatively little variation, remaining within approximately 5.70–5.82 cm. However, rather than interpreting this increase as a direct physiological benefit of storage, it is more appropriate to consider it in the context of the coating × storage interaction and genotype-specific growth responses. Indeed, the highest seedling length was recorded for coated Gregoria after transportation (6.91 cm), whereas the lowest value was observed for uncoated Balboa after storage (5.10 cm), highlighting the biological relevance of the three-way interaction (Table 2). Overall, although seed coating can increase seedling length in sugar beet, the dependence of this response on cultivar and storage/transportation stage indicates that coating technologies should be optimized on a cultivar-specific basis to improve early seedling development.

Root Length

The significant effects of the main factors of coating, storage, and cultivar, together with all two-way and three-way interactions, on root length indicate that root development in sugar beet is jointly influenced by genotype, seed processing technology, and storage conditions (Table 1). Seed coating reduced root length from 9.03 cm in uncoated seeds to 8.15 cm in coated seeds, corresponding to a decrease of approximately 9.75% (Table 2). This reduction may reflect coating-induced changes in imbibition and oxygen diffusion, the physical resistance the coating layer imposes on radicle emergence, and the resulting restriction of early root elongation. Duan and Burris (1997) reported that seed coating in sugar beet could influence germination and early development by modifying the movement of water, oxygen, and inhibitory compounds, while Podlaski et al. (2019) demonstrated that pellet porosity,

mechanical strength, water resistance, and water potential are important determinants of early developmental performance. The higher germination and emergence performance reported for uncoated sugar beet seeds by Kulan and Kaya (2016) is also consistent with the present findings. Collectively, these results indicate that coating materials should be optimized not only for germination and emergence but also to avoid restricting early root system development.

Table 1. Mean squares from the analysis of variance for seedling traits of sugar beet cultivars under different coating treatments and storage stages

Source of Variation	DF	Seedling Length	Root Length	Vegetative Fresh Weight
Total	119			
Coating	1	0,877**	23,214**	0,0064**
Storage	2	1,525**	1,254**	0,0009**
Coating × Storage Int.	2	2,276**	1,017**	0,0006**
Cultivar	4	0,510**	4,392**	0,0053**
Cultivar × Coating Int.	4	2,119**	1,748**	0,0105**
Cultivar × Storage Int.	8	0,176	2,482**	0,0005**
Cultivar × Coating × Storage Int.	8	0,339**	2,192**	0,0010**
Error	90	0,093	0,087	0,0001
Source of Variation	**DF**	**Vegetative Dry Weight**	**Root Fresh Weight**	**Root Dry Weight**
Total	119			
Coating	1	0,00008*	0,0023**	0,0003**
Storage	2	0,00004	0,0013**	0,0008**
Coating × Storage Int.	2	0,00002	0,0008**	0,0004**
Cultivar	4	0,00006**	0,0007**	0,0006**
Cultivar × Coating Int.	4	0,00026**	0,0004**	0,0008**
Cultivar × Storage Int.	8	0,00005**	0,0013**	0,0005**
Cultivar × Coating × Storage Int.	8	0,00007**	0,0008**	0,0007**
Error	90	0,00002	0,0001	0,0000

*: $p<0.05$; **: $p<0.01$

Root Length

The significant effects of the main factors of coating, storage, and cultivar, together with all two-way and three-way interactions, on root length indicate that root development in sugar beet is jointly influenced by genotype, seed processing technology, and storage conditions (Table 1). Seed coating reduced root length from 9.03 cm in uncoated seeds to 8.15 cm in coated seeds, corresponding to a decrease of approximately 9.75% (Table 2). This reduction may reflect coating-induced changes in imbibition and oxygen diffusion, the physical resistance the coating layer imposes on radicle emergence, and the resulting restriction of early root elongation. Duan and Burris (1997) reported that seed coating in sugar beet could influence germination and early development by modifying the movement of water, oxygen, and inhibitory compounds, while Podlaski et al. (2019) demonstrated that pellet porosity, mechanical strength, water resistance, and water potential are important determinants of early developmental performance. The higher germination and emergence performance reported for uncoated sugar beet seeds by Kulan and Kaya (2016) is also consistent with the present findings. Collectively, these results indicate that coating materials should be optimized not only for germination and emergence but also to avoid restricting early root system development.

The effect of coating on root development varied markedly among cultivars, demonstrating the biological importance of the cultivar × coating interaction. Coating-induced reductions in root length were limited to 3.31% in Juncal and 4.11% in Gregoria, whereas the corresponding reductions reached 15.27% in Terranova and 14.39% in Preziosa. Nevertheless, when averaged across treatments, Preziosa (9.09 cm) and Balboa (9.00 cm) recorded the greatest root lengths, whereas Gregoria, Juncal, and Terranova showed lower and statistically similar values. These differences indicate that a genotype with

inherently high root growth potential may not maintain the same advantage after coating, and that tolerance to coating should therefore be evaluated independently of initial root growth capacity (Table 2). This interpretation is consistent with Mirzaei and Hemayati (2022), who reported that genotype and genotype × environment interactions significantly influenced early growth traits in sugar beet. Therefore, rather than adopting a uniform coating strategy, cultivar-specific optimization approaches that account for genotypic differences in physiological sensitivity to coating appear to be more appropriate.

Table 2. Mean seedling length (cm), root length (cm), and vegetative fresh weight (g) of sugar beet cultivars under different coating treatments and storage stages, with statistical groupings

Coating	Storage	Cultivars					Mean
		Balboa	Gregoria	Juncal	Preziosa	Terranova	
Seedling Length (cm)							
Uncoated	Before	5,45^{d-g}	5,69^{c-g}	5,90^{b-g}	6,22^{a-e}	5,83^{b-g}	5,82^{b}
	After	5,10^{g}	5,89^{b-g}	5,49^{c-g}	6,31^{abc}	5,73^{b-g}	5,70^{bc}
	Transportation	5,39^{efg}	5,68^{c-g}	5,24^{fg}	6,32^{abc}	6,07^{b-f}	5,74^{bc}
	Mean	5,31^{d}	5,75^{b}	5,54^{cd}	6,28^{a}	5,87^{bc}	5,75
Coated	Before	6,07^{b-f}	5,36^{fg}	5,24^{fg}	5,39^{efg}	5,28^{fg}	5,47^{c}
	After	6,53^{ab}	6,27^{a-d}	5,66^{c-g}	5,51^{c-g}	5,93^{b-g}	5,98^{b}
	Transportation	6,32^{abc}	6,91^{a}	6,28^{abc}	6,22^{a-e}	5,90^{b-g}	6,32^{a}
	Mean	6,30^{a}	6,18^{ab}	5,73^{c}	5,71^{cd}	5,70^{cd}	5,92
Mean	Before	5,76	5,52	5,57	5,80	5,56	5,64^{c}
	After	5,81	6,08	5,57	5,91	5,83	5,84^{b}
	Transportation	5,85	6,29	5,76	6,27	5,98	6,03^{a}
	Mean	5,81^{ab}	5,96^{a}	5,63^{b}	5,99^{a}	5,79^{ab}	5,84
Root Length (cm)							
Uncoated	Before	9,07^{c-f}	9,48^{bc}	8,53^{e-i}	9,41^{bcd}	9,39^{bcd}	9,18^{a}
	After	9,54^{bc}	8,76^{c-h}	8,25^{ghi}	9,44^{bc}	8,13^{hij}	8,83^{b}
	Transportation	9,94^{ab}	7,33^{jkl}	8,62^{d-h}	10,53^{a}	8,99^{c-g}	9,08^{ab}
	Mean	9,52^{a}	8,52^{bc}	8,47^{bc}	9,80^{a}	8,84^{b}	9,03
Coated	Before	9,25^{b-e}	8,13^{hij}	8,55^{e-i}	7,99^{hij}	8,09^{hij}	8,40^{c}
	After	9,48^{bc}	8,36^{f-i}	7,75^{ijk}	8,40^{f-i}	7,00^{kl}	8,20^{c}
	Transportation	6,73^{l}	8,04^{hij}	8,28^{f-i}	8,78^{c-h}	7,38^{jkl}	7,84^{d}
	Mean	8,49^{bc}	8,17^{c}	8,19^{c}	8,39 c	7,49^{d}	8,15
Mean	Before	9,16^{ab}	8,80^{bcd}	8,54^{cde}	8,70^{bcd}	8,74^{bcd}	8,79^{a}
	After	9,51^{a}	8,56^{cde}	8,00^{fgh}	8,92^{bc}	7,56^{h}	8,51^{b}
	Transportation	8,33^{def}	7,68^{gh}	8,45^{c-f}	9,66^{a}	8,18^{efg}	8,46^{b}
	Mean	9,00^{a}	8,35^{b}	8,33^{b}	9,09^{a}	8,16^{b}	8,59
Vegetative Fresh Weight (g)							
Uncoated	Before	0,276^{gh}	0,335^{a-d}	0,284^{gh}	0,346^{ab}	0,335^{a-d}	0,315^{b}
	After	0,264^{h}	0,356^{a}	0,294^{efg}	0,341^{abc}	0,314^{def}	0,314^{b}
	Transportation	0,288^{fgh}	0,340^{a-d}	0,271^{gh}	0,347^{ab}	0,361^{a}	0,321^{b}
	Mean	0,276^{d}	0,344^{a}	0,283^{d}	0,345^{a}	0,336^{ab}	0,317
Coated	Before	0,336^{a-d}	0,341^{abc}	0,323^{bcd}	0,288^{fgh}	0,326^{bcd}	0,323^{b}
	After	0,350^{ab}	0,335^{a-d}	0,348^{ab}	0,316^{cde}	0,334^{a-d}	0,336^{a}
	Transportation	0,339^{a-d}	0,349^{ab}	0,334^{a-d}	0,336^{a-d}	0,317^{cde}	0,335^{a}
	Mean	0,341^{a}	0,342^{a}	0,335^{ab}	0,313^{c}	0,325^{bc}	0,331
Mean	Before	0,306^{fg}	0,338^{abc}	0,303^{g}	0,317^{d-g}	0,330^{a-d}	0,319^{b}
	After	0,307^{efg}	0,345^{a}	0,321^{c-f}	0,329^{a-d}	0,324^{b-e}	0,325^{a}
	Transportation	0,314^{d-g}	0,344^{a}	0,302^{g}	0,341^{a}	0,339^{ab}	0,328^{a}
	Mean	0,309^{c}	0,343^{a}	0,309^{c}	0,329^{b}	0,331^{b}	0,324

[1]Means followed by the same letter are not significantly different.

Storage and transportation also adversely affected root development, with mean root length decreasing from 8.79 cm before storage to 8.51 cm after storage and 8.46 cm after transportation. However, the coating × storage interaction indicated that this reduction was more pronounced in coated seeds. After transportation, root length decreased by only 1.09% in uncoated seeds, whereas it fell by 6.67% in coated seeds. Within the three-way interaction, uncoated Preziosa exhibited the greatest root length after transportation (10.53 cm), whereas coated Balboa showed the lowest value at the same stage (6.73 cm), clearly demonstrating that the effect of transportation varied substantially depending on both coating treatment and cultivar (Table 2). Taken together with the storage-related losses in physiological seed quality reported by Śliwińska (2003) and Gürel (2020), these findings suggest that maintaining root development in sugar beet requires integrated optimization of coating material physical properties, genotypic sensitivity, and storage/transportation conditions. In particular, post-transportation performance of coated seeds may represent an important criterion when evaluating seed quality for commercial use.

Vegetative Fresh Weight

The significant effects of coating, storage, and cultivar, together with all two-way and three-way interactions, on vegetative fresh weight indicate that seedling biomass accumulation in sugar beet is jointly influenced by genotype, seed processing treatment, and storage conditions (Table 1). Seed coating increased vegetative fresh weight from 0.317 g in uncoated seeds to 0.331 g in coated seeds, corresponding to an increase of approximately 4.42%. Despite the reductions previously observed in germination and emergence traits, this response suggests that coating may promote biomass accumulation in seedlings that successfully continue their development (Table 2). This finding is consistent with previous studies reporting beneficial effects of appropriate seed treatments on post-germination seedling development. Chomontowski et al. (2020) reported that appropriate priming treatments could enhance early seedling development and biomass accumulation, particularly in low-vigor sugar beet seeds, while Capron et al. (2000) demonstrated that hydropriming and osmopriming could improve early growth performance. Similarly, Ignatz et al. (2019) reported that reducing ABA and other inhibitory compounds in the pericarp promoted normal seedling development, whereas Podlaski et al. (2019) emphasized that porosity, water potential, and other physical properties of coating materials are important determinants of early seedling performance. Therefore, the effects of coating on seedling biomass should be evaluated not merely in terms of the presence or absence of a coating layer but also in relation to the physical properties of the coating material and the physiological response of the seed following coating.

The effect of coating on vegetative fresh weight varied markedly among cultivars in both magnitude and direction. Coating increased vegetative fresh weight by approximately 23.55% in Balboa and 18.37% in Juncal, whereas reductions of 0.58%, 9.28%, and 3.27% were observed in Gregoria, Preziosa, and Terranova, respectively. In particular, vegetative fresh weight in Balboa increased from 0.276 g in uncoated seeds to 0.341 g in coated seeds, indicating a strong positive biomass response to coating in this cultivar. In contrast, the decrease from 0.345 to 0.313 g in Preziosa demonstrates that the same coating treatment may produce contrasting responses among genotypes (Table 2). Across cultivars, Gregoria had the highest mean vegetative fresh weight (0.343 g), whereas Balboa and Juncal had the lowest mean values (0.309 g). The findings of Mirzaei and Hemayati (2022), who reported significant effects of genotype and genotype × environment interactions on early growth traits in sugar beet, are consistent with this cultivar-dependent variation. These results indicate that the effect of coating on biomass accumulation is genotype-specific and that cultivar × coating compatibility should be a key optimization criterion in commercial seed-coating applications.

Storage and transportation did not reduce vegetative fresh weight; instead, the overall mean increased from 0.319 g before storage to 0.325 g after storage and 0.328 g after transportation. This trend was particularly evident in coated seeds, for which vegetative fresh weight increased from 0.323 g before storage to 0.336 g after storage and remained at 0.335 g after transportation, whereas uncoated seeds showed no statistically significant change among storage stages. However, rather than interpreting this increase as a direct stimulatory effect of storage, it is more appropriate to consider it as the outcome of the combined effects of coating, genotype, and storage stage. Indeed, within the three-way interaction, uncoated Terranova recorded the highest vegetative fresh weight after transportation (0.361 g), whereas uncoated Balboa showed the lowest value after storage (0.264 g), clearly demonstrating the importance

of genotype-specific responses (Table 2). Overall, the response of vegetative fresh biomass to coating and storage/transportation processes in sugar beet varied substantially among cultivars, indicating that coating materials, cultivar characteristics, and storage conditions should be considered together when developing strategies to optimize early seedling growth.

Vegetative Dry Weight

Although vegetative dry weight was significantly affected by coating and cultivar, the nonsignificant main effect of storage indicates that dry matter accumulation in sugar beet was influenced more strongly by genotype and seed processing treatment than by storage stage itself (Table 1). Seed coating increased vegetative dry weight from 0.019 g in uncoated seeds to 0.021 g in coated seeds, corresponding to an increase of approximately 10.53%, suggesting that coating may promote seedling dry matter accumulation under appropriate conditions (Table 3). Capron et al. (2000) and Chomontowski et al. (2020) reported that appropriate seed treatments and priming techniques could improve early seedling development and biomass accumulation in sugar beet, while Ignatz et al. (2019) demonstrated that reducing ABA and other inhibitory compounds in the pericarp could promote normal seedling development. Similarly, Podlaski et al. (2019) reported that the porosity, water potential, and other physical properties of coating materials may influence post-germination seedling performance. These findings indicate that the effects of coating on early development should not be evaluated solely on the basis of germination or emergence performance; post-germination dry matter accumulation should also be considered.

The effect of coating on vegetative dry weight differed among cultivars in both direction and magnitude, clearly demonstrating the importance of the cultivar × coating interaction. Coating increased vegetative dry weight by approximately 33.33% in Juncal and 73.33% in Terranova, whereas reductions of 25.00% and 9.09% were observed in Balboa and Preziosa, respectively; no appreciable change occurred in Gregoria. Particularly, vegetative dry weight in Terranova increased from 0.015 g in uncoated seeds to 0.026 g in coated seeds, indicating a strong positive response to coating in terms of dry matter accumulation. In contrast, the reduction from 0.024 to 0.018 g in Balboa suggests that coating may induce contrasting physiological responses by genotype (Table 3). The findings of Duan and Burris (1997), who reported that responses to coating treatments may vary among sugar beet genotypes and seed lots, together with those of Mirzaei and Hemayati (2022), who emphasized genotypic variation in early growth traits, are consistent with the present results. Therefore, rather than adopting a uniform coating approach to improve vegetative dry matter accumulation, cultivar-specific strategies that account for individual genotypes' physiological responses to coating appear more appropriate.

Although the main effect of storage on vegetative dry weight was not statistically significant, the significant cultivar × storage and cultivar × coating × storage interactions indicate that the response to storage cannot be evaluated independently of cultivar and coating status. Mean vegetative dry weight increased from 0.019 g before storage to 0.021 g after storage and subsequently returned to 0.019 g after transportation, suggesting that storage and transportation did not result in an overall and persistent reduction in dry matter accumulation. However, coated Terranova reached 0.031 g after storage, the highest value among all treatment combinations, and coated Juncal reached 0.026 g, whereas coated Balboa exhibited the lowest value at the same stage (0.014 g). These contrasting responses demonstrate that the effect of storage was strongly dependent on the specific cultivar × coating combination (Table 3). Śliwińska (2003) reported that responses to storage and seed aging depend on initial seed quality, while Tohidloo et al. (2015) indicated that appropriately processed sugar beet seeds may retain their seedling establishment performance after storage, supporting the cultivar- and treatment-dependent variation observed in the present study. Overall, maintaining or enhancing vegetative dry matter accumulation in sugar beet requires the integrated consideration of coating material properties, genotypic responses, and storage conditions, emphasizing the importance of cultivar-specific optimization of seed-coating technologies.

Root Fresh Weight

The significant effects of coating, storage, and cultivar, together with all two-way and three-way interactions, on root fresh weight indicate that root biomass accumulation in sugar beet is jointly influenced by genotype, seed processing treatment, and storage conditions (Table 1). Seed coating increased root fresh weight from 0.082 g in uncoated seeds to 0.091 g in coated seeds, corresponding to an increase of approximately 10.98%. Despite the restrictive effects of coating previously observed for

germination and emergence traits, this increase suggests that coating may promote root biomass accumulation in seedlings that continue developing successfully (Table 3). Capron et al. (2000) and Chomontowski et al. (2020) reported that appropriate seed treatments and priming techniques could promote early seedling development in sugar beet, while Ignatz et al. (2019) demonstrated that reducing ABA and other inhibitory compounds in the pericarp could improve normal seedling development. Similarly, Podlaski et al. (2019) reported that porosity, water potential, and other physical properties of coating materials may be important determinants of post-germination seedling development. These findings indicate that coating effects on root development should be evaluated not only in terms of root length but also in relation to root biomass accumulation.

Although coating increased root fresh weight in all cultivars, the magnitude of this response varied considerably among genotypes. Following coating, root fresh weight increased by 11.25% in Balboa, 6.98% in Gregoria, 3.57% in Juncal, and 2.17% in Preziosa, whereas the increase reached 34.33% in Terranova. In particular, Terranova, which had the lowest root fresh weight in uncoated seeds (0.067 g), increased to 0.090 g after coating, indicating a strong positive response to coating in root biomass accumulation. Nevertheless, across overall cultivar means, Preziosa had the highest root fresh weight (0.093 g), whereas Terranova had the lowest (0.079 g) (Table 3). The findings of Duan and Burris (1997), who reported that responses to coating treatments may vary among sugar beet genotypes and seed lots, together with those of Mirzaei and Hemayati (2022), who emphasized genotypic differences in early growth traits, are consistent with the present results. Therefore, in addition to the overall effect of coating, consider cultivar × coating compatibility when seeking to improve root biomass accumulation, and optimize coating treatments according to genotype-specific responses.

Table 3. Mean vegetative dry weight (g), root fresh weight (g), and root dry weight (g) of sugar beet cultivars under different coating treatments and storage stages, with statistical groupings

Coating	Storage	Cultivars					Mean
		Balboa	Gregoria	Juncal	Preziosa	Terranova	
Dry Weight (g)							
Uncoated	Before	0,026^{ab}	0,015^{cd}	0,015^{cd}	0,025^{abc}	0,015^{cd}	0,019
	After	0,024^{a-d}	0,019^{bcd}	0,016^{bcd}	0,023^{a-d}	0,016^{bcd}	0,020
	Transportation	0,022^{a-d}	0,022^{a-d}	0,015^{cd}	0,017^{bcd}	0,015^{cd}	0,018
	Mean	0,024^{ab}	0,019^{cd}	0,015^{d}	0,022^{abc}	0,015^{d}	0,019
Coated	Before	0,019^{bcd}	0,018^{bcd}	0,016^{bcd}	0,020^{a-d}	0,024^{a-d}	0,019
	After	0,014^{d}	0,025^{a-d}	0,026^{ab}	0,016^{bcd}	0,031^{a}	0,022
	Transportation	0,021^{a-d}	0,015^{cd}	0,018^{bcd}	0,024^{a-d}	0,024^{a-d}	0,020
	Mean	0,018^{cd}	0,019^{bcd}	0,020^{bcd}	0,020^{bcd}	0,026^{a}	0,021
Mean	Before	0,023^{abc}	0,016^{bc}	0,016^{c}	0,023^{ab}	0,020^{abc}	0,019
	After	0,019^{abc}	0,022^{abc}	0,021^{abc}	0,019^{abc}	0,024^{a}	0,021
	Transportation	0,022^{abc}	0,018^{abc}	0,016^{bc}	0,020^{abc}	0,019^{abc}	0,019
	Mean	0,021^{a}	0,019^{ab}	0,018^{b}	0,021^{ab}	0,021^{ab}	0,020
Root Fresh Weight (g)							
Uncoated	Before	0,080^{b}	0,084^{ab}	0,085^{ab}	0,100^{ab}	0,103^{ab}	0,090^{ab}
	After	0,075^{b}	0,091^{ab}	0,084^{ab}	0,084^{ab}	0,084^{ab}	0,084^{b}
	Transportation	0,083^{ab}	0,084^{ab}	0,083^{b}	0,092^{ab}	0,015^{c}	0,071^{c}
	Mean	0,080^{bc}	0,086^{ab}	0,084^{ab}	0,092^{ab}	0,067^{c}	0,082
Coated	Before	0,094^{ab}	0,101^{ab}	0,087^{ab}	0,095^{ab}	0,093^{ab}	0,094^{a}
	After	0,089^{ab}	0,093^{ab}	0,086^{ab}	0,077^{b}	0,092^{ab}	0,087^{ab}
	Transportation	0,084^{ab}	0,083^{b}	0,090^{ab}	0,111^{a}	0,084^{ab}	0,090^{ab}
	Mean	0,089^{ab}	0,092^{ab}	0,087^{ab}	0,094^{a}	0,090^{ab}	0,091
Mean	Before	0,087^{ab}	0,092^{ab}	0,086^{ab}	0,098^{ab}	0,098^{ab}	0,092^{a}
	After	0,082^{b}	0,092^{ab}	0,085^{ab}	0,080^{b}	0,088^{ab}	0,086^{b}
	Transportation	0,084^{ab}	0,083^{b}	0,086^{ab}	0,101^{a}	0,050^{c}	0,081^{b}
	Mean	0,084^{bc}	0,089^{ab}	0,086^{abc}	0,093^{a}	0,079^{c}	0,086
Root Dry Weight (g)							

Uncoated	Before	0,016^{b}	0,015^{b}	0,015^{b}	0,016^{b}	0,014^{b}	0,015^{c}
	After	0,017^{b}	0,018^{b}	0,017^{b}	0,017^{b}	0,016^{b}	0,017^{bc}
	Transportation	0,084^{a}	0,016^{b}	0,017^{b}	0,015^{b}	0,016^{b}	0,030^{a}
	Mean	0,039^{a}	0,016^{c}	0,016^{c}	0,016^{c}	0,015^{c}	0,021
Coated	Before	0,016^{b}	0,025^{b}	0,015^{b}	0,015^{b}	0,017^{b}	0,017^{bc}
	After	0,017^{b}	0,017^{b}	0,017^{b}	0,015^{b}	0,016^{b}	0,016^{bc}
	Transportation	0,015^{b}	0,024^{b}	0,018^{b}	0,022^{b}	0,017^{b}	0,019^{b}
	Mean	0,016^{c}	0,022^{b}	0,016^{c}	0,018^{bc}	0,017^{c}	0,018
Mean	Before	0,016^{b}	0,020^{b}	0,015^{b}	0,015^{b}	0,016^{b}	0,016^{b}
	After	0,017^{b}	0,018^{b}	0,017^{b}	0,016^{b}	0,016^{b}	0,017^{b}
	Transportation	0,050^{a}	0,020^{b}	0,018^{b}	0,019^{b}	0,016^{b}	0,024^{a}
	Mean	0,027^{a}	0,019^{b}	0,016^{bc}	0,017^{bc}	0,016^{c}	0,019

[1]Means followed by the same letter are not significantly different.

Storage and transportation reduced root fresh weight, with the overall mean decreasing from 0.092 g before storage to 0.086 g after storage and 0.081 g after transportation, corresponding to reductions of approximately 6.52% and 11.96%, respectively, relative to the pre-storage value. However, this reduction was more pronounced in uncoated seeds, in which root fresh weight decreased from 0.090 g before storage to 0.071 g after transportation, whereas coated seeds exhibited only a limited decrease from 0.094 to 0.090 g. This pattern suggests that coating may help maintain root biomass during storage and transportation. Nevertheless, in the three-way interaction, coated Preziosa showed the highest root fresh weight after transportation (0.111 g), whereas uncoated Terranova showed the lowest value at the same stage (0.015 g), demonstrating that the apparent protective effect of coating was strongly genotype-dependent (Table 3). Together with the storage-related physiological changes reported by Śliwińska (2003) and Gürel (2020), these findings indicate that maintaining and improving root fresh biomass in sugar beet requires integrated consideration of coating material properties, genotypic sensitivity, and storage/transportation conditions. In particular, consider cultivar × coating compatibility when evaluating seed performance after transportation.

Root Dry Weight

The significant effects of coating, storage, and cultivar, together with all two-way and three-way interactions, on root dry weight indicate that root dry matter accumulation in sugar beet is jointly influenced by genotype, seed processing treatment, and storage conditions (Table 1). Seed coating reduced root dry weight from 0.021 g in uncoated seeds to 0.018 g in coated seeds, corresponding to a decrease of approximately 14.29%. This reduction may reflect coating-induced changes in imbibition, oxygen diffusion, and radicle development, which could limit root dry matter accumulation during early seedling growth (Table 3). Duan and Burris (1997) reported that coating may alter the movement of water, oxygen, and inhibitory compounds in sugar beet seeds, while Podlaski et al. (2019) demonstrated that pellet porosity, water resistance, and water potential are important determinants of early seedling performance. In contrast, Capron et al. (2000) and Chomontowski et al. (2020) reported that appropriate seed treatments and priming techniques could promote early seedling development and biomass accumulation. These contrasting findings indicate that the effects of coating on root dry matter accumulation should be interpreted in relation to both the coating's physical characteristics and the genotype's physiological response.

The direction and magnitude of the response to coating varied among cultivars, demonstrating that the cultivar × coating interaction was an important determinant of root dry weight. Coating reduced root dry weight by approximately 58.97% in Balboa, whereas Gregoria, Preziosa, and Terranova showed increases of 37.50%, 12.50%, and 13.33%, respectively; Juncal showed no appreciable change. In particular, Balboa showed the highest root dry weight under the uncoated treatment (0.039 g), but it decreased to 0.016 g after coating, indicating a strong negative response to coating. In contrast, the increase from 0.016 to 0.022 g in Gregoria suggests that coating may promote root dry matter accumulation in some genotypes (Table 3). The findings of Mirzaei and Hemayati (2022), who reported that early growth traits in sugar beet were significantly influenced by genotype and genotype × environment interactions, are consistent with this cultivar-dependent variation. Therefore, when the objective is to maintain root dry matter accumulation, coating treatments should not be evaluated

independently of genotype, and cultivar × coating compatibility should be considered an important selection criterion in seed processing strategies.

Although overall root dry weight was 0.016 g before storage and 0.017 g after storage and increased to 0.024 g after transportation, the interaction results indicate that this increase was largely attributable to a specific cultivar × treatment combination rather than to a general beneficial effect of transportation. In uncoated Balboa, root dry weight increased from 0.016 g before storage and 0.017 g after storage to 0.084 g after transportation. In contrast, values for coated Balboa remained within a narrow range of 0.015–0.017 g across all stages, while changes in the other cultivars were generally limited. Therefore, the approximately 50% increase in the overall mean observed after transportation should be interpreted as a strong response specific to the Balboa × uncoated × transportation combination rather than as a general transportation effect applicable to all cultivars (Table 3). The genotype-, initial seed quality-, and seed processing-dependent responses to storage reported by Śliwińska (2003), Tohidloo et al. (2015), and Kulan and Kaya (2016) support this interpretation. Overall, evaluating root dry weight in sugar beet should not rely solely on main-effect means; cultivar × coating × storage interactions should also be considered, and unusually strong genotype-specific responses should be distinguished from general treatment trends.

CONCLUSION

This study showed that the effects of seed coating, storage, and transportation on early seedling development in sugar beet varied substantially by trait and cultivar. Overall, seed coating increased seedling length and vegetative fresh and dry weight, while reducing root length and root dry weight; in contrast, root fresh weight increased following coating, indicating contrasting responses among different components of shoot and root development. The marked differences in coating responses among Balboa, Gregoria, Juncal, Preziosa, and Terranova, along with the significance of numerous cultivar × coating × storage/transportation interactions, indicate that a uniform coating and storage strategy may not suit all cultivars equally. Storage and transportation also affected the evaluated traits differently. Reductions were particularly evident in root length and root fresh weight, whereas some biomass traits were maintained or increased depending on cultivar and coating status. Overall, maintaining high and balanced early seedling performance in commercial sugar beet seeds requires cultivar-specific optimization of the physical and physiological properties of coating materials, management of storage and transportation conditions with consideration of cultivar × coating interactions, and an integrated assessment of shoot growth, root development, and biomass accumulation rather than reliance on a single growth trait.

ACKNOWLEDGMENTS

This study was supported by the Scientific Research Projects Coordination Unit of Selçuk University under Project No. 25201027. This study was prepared as part of the M.Sc. thesis conducted by Hamza DOĞAN at the Department of Field Crops, Graduate School of Natural and Applied Sciences, Selçuk University.

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EFFECTS OF SEED COATING, STORAGE AND TRANSFER PROCESSES ON EARLY SEEDLING DEVELOPMENT AND BIOMASS ACCUMULATION IN DIFFERENT ALFALFA CULTIVARS

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ABSTRACT
Rapid, balanced seedling development is critical for uniform stand establishment and successful crop establishment in alfalfa. This study aimed to determine the effects of seed coating, storage, and transfer processes on early seedling development and biomass traits in different alfalfa cultivars. Uncoated and coated seeds prepared at a 1:1 coating ratio from five cultivars, Bilensoy, Blue Ace, Bolton, Icon, and Sunter, were evaluated before storage, after approximately six months of storage at 5 °C and 60% relative humidity, and following the transfer period. Seedling length, root length, vegetative fresh and dry weight, and root fresh and dry weight were assessed. Seed coating, storage, cultivar, and their interactions significantly affected seedling development traits. Coating increased mean seedling length from 5.92 to 6.17 cm, corresponding to an increase of approximately 4.22%. Mean seedling length increased from 5.25 cm before storage to 6.44 cm after storage and remained nearly stable at 6.43 cm after transfer. Icon showed the highest overall seedling length (6.29 cm), while the highest individual value, 7.36 cm, was recorded in coated Icon seeds after storage. In contrast, coating reduced mean root length from 5.44 to 5.23 cm, while storage decreased root length from 6.42 cm before storage to 4.61 cm after storage, followed by partial recovery to 4.96 cm after transfer. Coating increased vegetative dry weight by approximately 10% and root fresh weight by 53.19%, whereas root dry weight decreased by 45.45%. Overall, seed coating promoted shoot development and selected biomass components, whereas its effects on root development varied according to cultivar and storage stage. These findings indicate that coating and storage protocols should be optimized on a cultivar-specific basis to maintain balanced early seedling development in commercial alfalfa seed production.
Keywords: Biomass, Seed Coating, Seedling Development, Storage, Transportation.

INTRODUCTION
Alfalfa (*Medicago sativa* L.) is considered one of the most important forage crops worldwide because of its high forage quality, perennial growth habit, broad adaptability, and ecological and agronomic contributions to agricultural production systems through symbiotic nitrogen fixation (Rocha et al., 2019; Zhang et al., 2022). The establishment of a persistent and highly productive alfalfa stand depends not only on seed viability but also on the rapid development of vigorous and normal seedlings following germination. The early seedling stage represents one of the most sensitive phases of plant development to environmental conditions, and morphological and physiological differences occurring during this period may substantially influence subsequent stand establishment (Rajjou et al., 2012). Therefore, traits such as seedling length, root length, the capacity to produce normal seedlings, and root and shoot fresh and dry weights are important indicators for evaluating seed vigor and early plant performance (Afzal et al., 2020; Rajjou et al., 2012).
Early seedling development results from coordinated physiological processes involving seed reserve mobilization and the formation of root and shoot tissues. After the seed takes up water, metabolic activity resumes, protein synthesis begins, cellular repair mechanisms activate, and stored reserves mobilize toward the embryonic axis, providing the physiological basis for seedling development (Rajjou et al., 2012). Rapid root development improves access to water and nutrients, whereas shoot development promotes the formation of photosynthetically active tissues and the transition from heterotrophic development to autotrophic growth. In contrast, physiological deterioration from seed aging or

environmental stresses may impair efficient utilization of stored reserves, resulting in reduced root and shoot elongation, lower biomass accumulation, and increased abnormal seedling formation. Therefore, integrating early seedling traits provides a more comprehensive assessment of a seed lot's physiological status than evaluating a single trait alone.

Seed-coating technologies have become an important component of modern seed technology because they can enhance early seedling development and crop establishment. Beyond forming a physical layer on the seed surface, coating materials can facilitate the controlled delivery of nutrients, biostimulants, plant protection products, and beneficial microorganisms in the immediate vicinity of the developing seedling (Afzal et al., 2020; Paravar et al., 2023). Appropriate coating formulations may positively influence root and shoot development by modifying the seed microenvironment and facilitating water and nutrient use during early growth. Studies conducted in alfalfa have demonstrated that different seed treatments can promote root development, seedling growth, and biomass accumulation, particularly under stress conditions; however, the magnitude and direction of these responses may vary depending on application rate, coating composition, genotype, and environmental conditions (Bıçakcı et al., 2018; Arslan et al., 2020; Öten and Tuzlacı, 2024). Conversely, inappropriate physical or chemical properties of the coating layer may alter water and gas exchange between the seed and its environment, thereby constraining early seedling development. Consequently, evaluate the effects of coating treatments on seedling performance in relation to both cultivar and application conditions (Qiu et al., 2020; Sprey et al., 2025).

Evaluation of the seedling establishment capacity of coated seeds solely on the basis of their initial performance immediately after coating may not adequately represent the actual conditions encountered by commercial seed lots. After coating, seeds are typically stored for varying periods and then transported before reaching the sowing site. Physiological aging during storage, influenced by temperature, relative humidity, and particularly seed moisture content, may reduce seed vigor by deteriorating membrane integrity, protein structure, DNA integrity, and cellular repair mechanisms (Rajjou and Debeaujon, 2008; Rajjou et al., 2012). The consequences of vigor loss may become apparent before complete loss of viability through reduced root and shoot growth, decreased capacity to produce normal seedlings, and lower seedling biomass. In addition, the moisture balance, mechanical integrity, and storage stability of coating materials may modify the response of coated seeds to storage, while environmental and physical stresses encountered during transportation may impose additional stress on seeds already affected by storage-related physiological changes (Afzal et al., 2020; Paravar et al., 2023; Sprey et al., 2025). These considerations highlight the need to evaluate coating × storage × transportation interactions in relation to early seedling development.

This study aimed to determine changes in early seedling growth performance in coated and uncoated seeds of different alfalfa cultivars before storage, after storage, and after storage plus transportation. Specifically, the study aimed to determine the individual and interactive effects of cultivar, seed coating, and storage/transportation processes on seedling length, root length, vegetative fresh and dry weight, and root fresh and dry weight. Comparing seedling growth responses among alfalfa cultivars that differ in genetic background and dormancy characteristics with coating and storage conditions is particularly important for identifying physiological changes in seed vigor that may not be detectable through final viability measurements alone. Accordingly, the study aimed to determine whether coating effects on early seedling development were maintained throughout storage and transportation and to characterize cultivar-specific responses to these processes. The findings are expected to provide a scientific basis for optimizing the commercial storage and distribution of coated alfalfa seeds and maintaining high seedling establishment potential before sowing.

MATERIALS AND METHODS

Plant Material

This study was conducted during 2024–2025 in the laboratories of the Ankara Seed Registration and Certification Directorate to determine changes in seed viability and germination performance of uncoated and coated alfalfa (*Medicago sativa* L.) seeds before storage, after storage, and after storage plus transportation. Seeds of five alfalfa cultivars representing different dormancy groups—Bilensoy-80, Blue Ace, Bolton, Icon, and Sunter—were used as plant material. Seeds from the same seed lot of each cultivar were divided into two groups, coated and uncoated, to allow direct comparison of coating

treatments. Seed coating was performed by ABEL Tohumculuk A.Ş. at a 1:1 (w/w) ratio, corresponding to the application of 1 kg of coating material per 1 kg of seed.

The cultivars differed in dormancy level and agronomic characteristics. Bilensoy-80 (dormancy group 4) is characterized by its adaptation to the Central Anatolian and Transitional Regions and its tolerance to winter conditions, drought, and lodging. Blue Ace (dormancy group 9) is characterized by a semi-erect growth habit, fine stems, a high leaf-to-stem ratio, strong seedling vigor, and adaptation to hot and dry conditions. Bolton (dormancy group 5) is characterized by high fresh and dry forage yields and high crude protein content. Icon (dormancy group 6) is distinguished by high seedling vigor and a high leaf-to-stem ratio, together with resistance to lodging, Fusarium, and Phytophthora. Sunter (dormancy group 5–7) is characterized by a strong and deep root system, rapid regrowth capacity, high forage yield potential, and tolerance to adverse winter conditions. Thus, cultivars differing in genetic and agronomic characteristics and dormancy levels enabled comparative evaluation of their physiological responses to seed coating, storage, and transportation.

Methods

Seed Physiological Quality Before Storage

To determine seed physiological quality before storage, seeds obtained from harvested plants that had not yet been subjected to any storage or transportation process were used. Standard germination tests were conducted in accordance with the rules of the International Seed Testing Association (ISTA) to determine the initial physiological quality of the seeds. Seedling length, root length, and fresh and dry biomass accumulation were determined. These values served as baseline data for evaluating changes after storage and transportation (ISTA, 2025).

Seed Physiological Quality After Storage

To determine the effects of storage on seed physiological quality and early seedling development, seeds were stored for approximately six months at +5 °C and 60% relative humidity. After the storage period, the physiological quality characteristics of the seeds were reassessed in accordance with ISTA rules. Standard germination tests were conducted, and seedling length, root length, and fresh and dry biomass accumulation were determined. The results were compared with the pre-storage values to evaluate the effects of the six-month storage period on seed physiological quality and early seedling development (ISTA, 2025).

Seed Physiological Quality After Storage and Transportation

To determine the effects of post-storage transportation on seed performance, seeds stored for approximately six months at +5 °C and 60% relative humidity underwent a 16-h transportation period after storage. Following transportation, seed physiological quality and early seedling growth performance were evaluated in accordance with ISTA rules. Seedling length, root length, and fresh and dry biomass accumulation were determined. The resulting data were compared with those obtained before and after storage to evaluate the sequential effects of storage and subsequent transportation on seed physiological quality and early seedling development (ISTA, 2025).

Statistical Analysis

Data from the study were analyzed using analysis of variance (ANOVA) in JMP statistical software. When ANOVA detected significant effects or interactions, means were compared using Tukey's Honestly Significant Difference (HSD) multiple-comparison test in JMP (JMP, 2023). Statistical significance was evaluated at the 5% probability level ($p < 0.05$), and differences among means were indicated by letter groupings.

RESULTS AND DISCUSSION

Seedling Length

Analysis of variance revealed that seedling length in alfalfa was significantly affected by the main effects of coating, storage, and cultivar, as well as by all two-way and three-way interactions ($p < 0.01$) (Table 1). Overall, seed coating increased seedling length from 5.92 cm in uncoated seeds to 6.17 cm in coated seeds, an increase of approximately 4.22%. Across storage stages, mean seedling length increased from 5.25 cm before storage to 6.44 cm after storage and remained nearly unchanged at 6.43 cm after transportation, with the latter two stages in the same statistical group. The coating × storage

interaction showed that this response differed by coating status. In uncoated seeds, seedling length increased from 5.02 cm before storage to 6.49 cm after storage and subsequently decreased to 6.25 cm after transportation. In coated seeds, the corresponding values were 5.49, 6.39, and 6.62 cm, respectively. Thus, the advantage of coating was particularly evident after transportation, when coated seeds showed the greatest mean seedling length. However, the increase in seedling length observed after storage should not be interpreted as evidence of a direct growth-promoting effect of storage. Rather, consider this response in relation to the physiological status of seeds that successfully germinated after storage, reserve mobilization, and genotype-specific growth capacity (Table 2).

Table 1. Mean squares from the analysis of variance for seedling traits of alfalfa cultivars under different coating treatments and storage stages

Source of Variation	DF	Seedling Length	Root Length	Vegetative Fresh Weight
Total	119			
Coating	1	1,820**	1,323**	0,0002**
Storage	2	18,660**	36,795**	0,0606**
Coating × Storage Int.	2	0,949**	0,695**	0,0031**
Cultivar	4	1,509**	0,951**	0,0055**
Cultivar × Coating Int.	4	0,068**	0,417**	0,0029**
Cultivar × Storage Int.	8	0,716**	0,651**	0,0043**
Cultivar × Coating × Storage Int.	8	0,487**	0,670**	0,0023**
Error	90	0,004	0,088	0,0000
Source of Variation	**DF**	**Vegetative Dry Weight**	**Root Fresh Weight**	**Root Dry Weight**
Total	119			
Coating	1	0,00000**	0,0179*	0,0010**
Storage	2	0,00010**	0,0924**	0,0024**
Coating × Storage Int.	2	0,00001**	0,0037	0,0013**
Cultivar	4	0,00001**	0,0130**	0,0012**
Cultivar × Coating Int.	4	0,00001**	0,0131**	0,0013**
Cultivar × Storage Int.	8	0,00001**	0,0120**	0,0012**
Cultivar × Coating × Storage Int.	8	0,00001**	0,0142**	0,0014**
Error	90	0,00000	0,0033	0,0000

*: $p<0.05$; **: $p<0.01$

RESULTS AND DISCUSSION

Seedling Length

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Marked genotypic differences in seedling length were observed, with Icon exhibiting the greatest overall mean (6.29 cm), followed by Blue Ace (6.20 cm), Sunter (6.12 cm), Bolton (5.96 cm), and Bilensoy (5.65 cm). Although coating increased seedling length in all cultivars, the magnitude of the response varied among genotypes. Relative to uncoated seeds, seedling length increased by 6.58% in Bilensoy, 5.22% in Icon, 4.46% in Bolton, 3.32% in Sunter, and 1.46% in Blue Ace. The cultivar × storage interaction also showed that cultivars differed in growth responses across storage stages; Icon reached the greatest value after storage (7.00 cm), whereas Blue Ace showed the greatest value after transportation (6.79 cm). The three-way interaction showed substantial variation among treatment combinations, ranging from 4.67 to 7.36 cm. The greatest seedling length was recorded for coated Icon after storage (7.36 cm), followed by coated Blue Ace after transportation (7.06 cm) and uncoated Blue Ace after storage (7.00 cm), whereas the lowest value was observed for uncoated Bolton before storage (4.67 cm). This pronounced interaction demonstrates that, although coating generally promoted seedling elongation, the magnitude of its effect depended on cultivar and storage stage. In particular, the high performance of coated Icon after storage and coated Blue Ace after transportation indicates that seedling development cannot be explained solely by the main effect of coating and that cultivar × coating × storage/transportation compatibility should also be considered (Table 2).

Table 2. Mean seedling length (cm), root length (cm), and vegetative fresh weight (g) of alfalfa cultivars under different coating treatments and storage stages, with statistical groupings

Coating	Storage	Cultivars					Mean
		Bilensoy	Blue Ace	Bolton	Icon	Sunter	
Seedling Length (cm)							
Uncoated	Before	4,94^{o}	4,94^{o}	4,67^{p}	5,65^{kl}	4,88^{o}	5,02^{f}
	After	5,48^{m}	7,00^{b}	6,68^{cd}	6,65^{c-f}	6,66^{cde}	6,49^{b}
	Transportation	5,99^{j}	6,52^{d-g}	6,14^{ij}	6,10^{ij}	6,51^{efg}	6,25^{d}
	Mean	5,47^{g}	6,15^{cd}	5,83^{f}	6,13^{d}	6,02^{e}	5,92
Coated	Before	5,25^{n}	5,51^{lm}	5,59^{lm}	5,63^{klm}	5,49^{lm}	5,49^{e}
	After	5,76^{k}	6,15^{ij}	6,23^{hi}	7,36^{a}	6,46^{g}	6,39^{c}
	Transportation	6,49^{fg}	7,06^{b}	6,45^{g}	6,37^{gh}	6,72^{c}	6,62^{a}
	Mean	5,83^{f}	6,24^{b}	6,09^{de}	6,45^{a}	6,22^{bc}	6,17
Mean	Before	5,10^{h}	5,23^{g}	5,13^{gh}	5,64^{f}	5,19^{gh}	5,25^{b}
	After	5,62^{f}	6,58^{c}	6,45^{d}	7,00^{a}	6,56^{cd}	6,44^{a}
	Transportation	6,24^{e}	6,79^{b}	6,29^{e}	6,24^{e}	6,61^{c}	6,43^{a}
	Mean	5,65^{e}	6,20^{b}	5,96^{d}	6,29^{a}	6,12^{c}	6,04
Root Length (cm)							
Uncoated	Before	5,46^{d-g}	6,16^{bcd}	6,45^{bc}	6,19^{bcd}	7,62^{a}	6,38^{a}
	After	4,67^{g-k}	4,92^{g-k}	5,14^{fgh}	4,46^{h-k}	4,85^{g-k}	4,81^{c}
	Transportation	5,09^{f-i}	5,26^{e-h}	5,19^{fgh}	5,07^{f-i}	5,04^{g-j}	5,13^{b}
	Mean	5,07^{cd}	5,45^{abc}	5,59^{ab}	5,24^{bcd}	5,84^{a}	5,44
Coated	Before	6,87^{ab}	6,73^{b}	5,86^{c-f}	6,06^{b-e}	6,82^{ab}	6,47^{a}
	After	4,29^{ijk}	4,17^{k}	4,78^{g-k}	4,23^{jk}	4,62^{h-k}	4,42^{d}
	Transportation	4,77^{g-k}	4,77^{g-k}	5,00^{g-j}	4,66^{g-k}	4,79^{g-k}	4,80^{c}
	Mean	5,31^{bcd}	5,22^{bcd}	5,21^{bcd}	4,98^{d}	5,41^{bc}	5,23
Mean	Before	6,17^{b}	6,45^{b}	6,16^{b}	6,12^{b}	7,22^{a}	6,42^{a}
	After	4,48^{ef}	4,55^{def}	4,96^{cde}	4,35^{f}	4,74^{c-f}	4,61^{c}
	Transportation	4,93^{cde}	5,02^{cd}	5,10^{c}	4,87^{cde}	4,92^{cde}	4,96^{b}
	Mean	5,19^{bc}	5,34^{bc}	5,40^{ab}	5,11^{c}	5,62^{a}	5,33
Vegetative Fresh Weight (g)							
Uncoated	Before	0,177^{lm}	0,187^{k}	0,174^{m}	0,177^{lm}	0,178^{lm}	0,179^{e}
	After	0,141^{o}	0,215^{h}	0,192^{ij}	0,211^{h}	0,192^{ij}	0,190^{d}
	Transportation	0,248^{d}	0,278^{b}	0,230^{f}	0,244^{de}	0,277^{b}	0,255^{a}
	Mean	0,189^{g}	0,226^{b}	0,198^{e}	0,211^{d}	0,216^{c}	0,208
Coated	Before	0,190^{jk}	0,180^{l}	0,223^{g}	0,189^{jk}	0,195^{i}	0,195^{c}
	After	0,150^{n}	0,126^{p}	0,152^{n}	0,222^{g}	0,212^{h}	0,172^{f}

	Transportation	0,240^{e}	0,271^{c}	0,174^{m}	0,285^{a}	0,269^{c}	0,248^{b}
	Mean	0,193^{f}	0,192^{f}	0,183^{h}	0,232^{a}	0,226^{b}	0,205
Mean	Before	0,184^{h}	0,183^{h}	0,199^{f}	0,183^{h}	0,187^{g}	0,187^{b}
	After	0,146^{j}	0,170^{i}	0,172^{i}	0,216^{d}	0,202^{e}	0,181^{c}
	Transportation	0,244^{c}	0,274^{a}	0,202^{e}	0,264^{b}	0,273^{a}	0,251^{a}
	Mean	0,191^{c}	0,209^{b}	0,191^{c}	0,221^{a}	0,221^{a}	0,207

[1]Means followed by the same letter are not significantly different.

The overall increase in seedling length associated with coating is consistent with previous reports indicating that appropriately designed coating systems may promote early seedling growth. Amirkhani et al. (2016, 2019) reported that plant-protein- and biostimulant-based coatings could improve early plant development, whereas Qiu et al. (2020) demonstrated that seedling responses may vary depending on coating formulation and plant species. Sprey et al. (2025) further emphasized that the physical and chemical properties of coating materials, particularly their water relations and storage stability, critically determine coating performance. The greater seedling length observed after storage in the present study may be related to physiological processes such as metabolic activation, maintenance of cellular integrity, and efficient mobilization of seed reserves during seedling growth, as emphasized by Rajjou et al. (2012). Nevertheless, the coating-induced increase was limited to 1.46% in Blue Ace but reached 6.58% in Bilensoy, indicating a strong genotypic component in the early seedling growth response. This interpretation is also consistent with Öten and Tuzlacı (2024), who reported that different priming and coating treatments could substantially modify early seedling development in alfalfa, and with Jabri et al. (2021) and Zhou et al. (2024), who demonstrated differential physiological responses of alfalfa genotypes to environmental conditions. Overall, coating increased seedling length, but cultivar and storage/transportation stage significantly modulated the magnitude of this effect. Therefore, coating technologies intended to improve early seedling development in alfalfa should be optimized according to cultivar and storage conditions rather than applied as a uniform, genotype-independent treatment.

The overall reduction in root length associated with coating indicates that seed-coating treatments do not invariably benefit early seedling development and that coating material, formulation, genotype, and environmental conditions should be considered jointly. Qiu et al. (2020) reported that the effects of seed coating on seedling development may vary depending on coating formulation and plant species, whereas Amirkhani et al. (2016, 2019) demonstrated that appropriately formulated biostimulant- and protein-based coatings could promote seedling development. These contrasting findings indicate that the biological effects of coatings are strongly modulated by coating material characteristics and application conditions. The coating thickness, physical integrity, water and gas exchange properties, and storage stability emphasized by Afzal et al. (2020) and Sprey et al. (2025) may also help explain the greater reduction in root length observed in coated seeds after storage in the present study. Furthermore, the decrease in root length from 6.42 cm before storage to 4.61 cm after storage indicates that root development was sensitive to storage-related physiological changes and is broadly consistent with the findings of Jungers et al. (2016) and Zhou et al. (2024), who reported that environmental conditions can substantially influence germination and early seedling development in alfalfa. The differential responses of root and early seedling traits to priming and coating treatments in alfalfa reported by Öten and Tuzlacı (2024) further support the cultivar × coating responses observed in the present study. Overall, greater initial root length did not necessarily confer greater tolerance to storage, nor did coating alone ensure superior root development. Instead, root growth maintenance appeared to depend on compatibility among genotype, coating material, and storage conditions. Therefore, when optimizing coating technologies for alfalfa, maintaining root development after storage should be considered an important vigor criterion alongside germination performance.

Vegetative Fresh Weight

Analysis of variance revealed that vegetative fresh weight in alfalfa was significantly affected by the main effects of coating, storage, and cultivar, as well as by all two-way and three-way interactions ($p < 0.01$) (Table 1). Across the overall means, seed coating reduced vegetative fresh weight from 0.208 g in uncoated seeds to 0.205 g in coated seeds, corresponding to a slight decrease of approximately 1.44%. In contrast, the effect of storage stage was considerably more pronounced. Vegetative fresh weight decreased from 0.187 g before storage to 0.181 g after storage and subsequently increased to 0.251 g

after transportation, representing an increase of approximately 34.22% relative to the pre-storage value. The coating × storage interaction also showed that this response differed by coating status. In uncoated seeds, vegetative fresh weight was 0.179, 0.190, and 0.255 g before storage, after storage, and after transportation, respectively, whereas in coated seeds it was 0.195, 0.172, and 0.248 g. Thus, coating was associated with greater fresh biomass before storage but with lower values after storage and transportation. Nevertheless, because both coated and uncoated seeds exhibited their greatest biomass after transportation, the variation in vegetative fresh weight appears to have been shaped primarily by the interaction between coating status and storage/transportation stage rather than by the main effect of coating alone (Table 2).

Cultivars differed significantly in their capacity for biomass accumulation. Across the overall means, Icon and Sunter had the highest vegetative fresh weight (0.221 g), Blue Ace an intermediate value (0.209 g), and Bilensoy and Bolton lower values (0.191 g). The response to coating was also strongly genotype-dependent. Among the cultivar × coating combinations, coated Icon exhibited the greatest value (0.232 g), whereas vegetative fresh weight in Blue Ace decreased from 0.226 g in uncoated seeds to 0.192 g following coating. The cultivar × storage interaction further showed that Blue Ace (0.274 g), Sunter (0.273 g), and Icon (0.264 g) exhibited pronounced biomass accumulation after transportation. The three-way interaction revealed even greater differentiation, with values ranging from 0.126 to 0.285 g. The greatest vegetative fresh weight was recorded for coated Icon after transportation (0.285 g), whereas the lowest value was observed for coated Blue Ace after storage (0.126 g). In particular, the increase in coated Blue Ace from 0.126 g after storage to 0.271 g after transportation, together with the maximum value of 0.285 g for coated Icon after transportation, shows that fresh biomass response to storage and transportation was nonlinear and strongly dependent on the cultivar × coating combination. Therefore, the relatively small overall effect of coating on vegetative fresh weight may mask pronounced positive or negative responses within specific cultivar and storage-stage combinations, indicating that treatment efficacy should not be evaluated solely on the basis of main-effect means (Table 2).

The relatively limited overall change in vegetative fresh weight associated with coating suggests that seed-coating technologies may not have a unidirectional effect on early seedling biomass and may vary by coating material, genotype, and environmental conditions. Amirkhani et al. (2016, 2019) reported that protein- and biostimulant-based coating systems can promote seedling development when appropriately formulated, whereas Qiu et al. (2020) showed that coating efficacy varies by formulation and plant species. Similarly, Afzal et al. (2020) emphasized that coating technologies can facilitate the targeted delivery of active ingredients to the seed microenvironment, but that coating material and application rate are critical for successful seedling establishment. Findings reported for alfalfa by Öten and Tuzlacı (2024) and Arslan et al. (2020) further support interpreting early growth responses to coating in conjunction with application and environmental conditions. In the present study, the relatively high biomass accumulation of Icon and Sunter, together with the contrasting coating responses observed in Icon and Blue Ace, indicates that genotypic variation was an important determinant of coating efficacy. This interpretation is consistent with Xie et al. (2023) and Zhou et al. (2024), who reported differential physiological responses among alfalfa genotypes during early seedling development. Sprey et al. (2025) also emphasized the importance of the physical and chemical properties of coating materials in understanding these genotype-specific responses. Overall, although the main effect of coating was limited to a 1.44% reduction in vegetative fresh weight, the marked difference between coated Icon after transportation (0.285 g) and coated Blue Ace after storage (0.126 g) demonstrates that early biomass accumulation was largely determined by cultivar × coating × storage/transportation compatibility. Therefore, coating technologies intended to improve biomass accumulation in alfalfa should be optimized by genotype and storage conditions rather than applied with a uniform treatment strategy.

Vegetative Dry Weight

Analysis of variance revealed that vegetative dry weight in alfalfa was significantly affected by the main effects of coating, storage, and cultivar, as well as by all two-way and three-way interactions ($p < 0.01$) (Table 1). Across the overall means, seed coating increased vegetative dry weight from 0.010 g in uncoated seeds to 0.011 g in coated seeds, corresponding to an increase of approximately 10%. A similar increasing trend was observed across storage stages, with dry weight increasing from 0.009 g before storage to 0.011 g after storage and 0.012 g after transportation. Thus, relative to the pre-storage value, dry matter accumulation increased by approximately 22.22% after storage and 33.33% after

transportation. However, the significant coating × storage interaction indicates that these changes cannot be explained by the independent effects of coating or storage alone. In contrast to the relatively limited effect of coating on fresh biomass, the increase in dry matter accumulation associated with coating suggests that coating may influence dry matter deposition and biomass allocation within seedling tissues differently from its effect on overall seedling size. Nevertheless, the greater dry weight values observed after storage and transportation should not be interpreted as evidence of a direct stimulatory effect of these processes. Rather, they should be considered in relation to the physiological performance of seedlings that successfully developed and the mobilization of seed reserves into seedling tissues (Table 3).

Cultivars differed significantly in their capacity for vegetative dry matter accumulation. Across the overall means, Sunter had the highest vegetative dry weight (0.012 g), followed by Blue Ace and Bolton (0.011 g), whereas Bilensoy and Icon had values of 0.010 g. Responses to coating were also genotype-dependent. Coating increased vegetative dry weight from 0.010 to 0.011 g in Bolton and from 0.009 to 0.011 g in Icon, whereas a slight reduction from 0.012 to 0.011 g was observed in Sunter; changes in Bilensoy and Blue Ace were comparatively limited. The cultivar × storage interaction showed that Blue Ace and Sunter reached 0.013 and 0.014 g, respectively, after transportation and were included in the highest statistical group, demonstrating that genotypes differed in their dry matter accumulation responses to storage and transportation. This variation became even more evident in the three-way interaction, with values ranging from 0.007 to 0.014 g across treatment combinations. The greatest vegetative dry weight was recorded for coated Blue Ace after transportation (0.014 g), while uncoated Blue Ace after storage and uncoated Sunter after transportation also exhibited high values of 0.014 g. The lowest value was observed for coated Bilensoy before storage (0.007 g). In particular, the increase in coated Blue Ace from 0.008 g before storage to 0.014 g after transportation and in coated Icon from 0.008 to 0.012 g demonstrates that the effect of coating varied substantially among genotypes depending on storage stage. Therefore, considering specific cultivar × coating × storage combinations, rather than relying on the overall coating mean alone, provides a more biologically meaningful interpretation of dry biomass accumulation (Table 3).

The increase in vegetative dry weight associated with coating is broadly consistent with previous studies indicating that appropriately designed seed-coating systems may promote early seedling development and biomass accumulation. Amirkhani et al. (2016) demonstrated the potential of biologically derived coating components to promote seedling and plant development, while Afzal et al. (2020) emphasized that modern coating technologies may improve seedling establishment by facilitating the targeted delivery of active ingredients to the seed microenvironment. In alfalfa, Öten and Tuzlacı (2024) similarly reported that different priming and coating treatments could modify germination and early seedling development, with seedling biomass traits varying substantially among treatments. Arslan et al. (2020) also demonstrated that coated alfalfa seeds may respond differently to environmental conditions, indicating that coating performance should not be evaluated independently of application conditions. In the present study, although coating increased overall vegetative dry weight by approximately 10%, the response was positive in Bolton and Icon but slightly negative in Sunter, indicating a strong genotypic component in the biomass response to coating. Furthermore, the increase in overall dry weight from 0.009 g before storage to 0.012 g after transportation, along with the highest value observed for the coated Blue Ace × after-transportation combination, demonstrates the dynamic nature of early seedling biomass responses to coating and storage/transportation. Overall, high and stable dry matter accumulation in alfalfa cannot be attributed solely to coated seeds; rather, the biological effectiveness of coating is substantially modulated by genotype and storage/transportation stage. Therefore, cultivar × coating × storage compatibility should be a key optimization criterion when using coating technologies to improve early seedling biomass accumulation in alfalfa.

Table 3. Mean vegetative dry weight (g), root fresh weight (g), and root dry weight (g) of alfalfa cultivars under different coating treatments and storage stages, with statistical groupings

Coating	Storage	Cultivars					Mean
		Bilensoy	Blue Ace	Bolton	Icon	Sunter	
Vegetative Dry Weight (g)							
Uncoated	Before	0,009^{hij}	0,009^{hi}	0,007^{kl}	0,008^{ijk}	0,010^{efg}	0,009^{c}

	After	0,010^{efg}	0,014^{abc}	0,011^{de}	0,010^{efg}	0,011^{de}	0,011^{b}
	Transportation	0,011^{ef}	0,011^{de}	0,011^{efg}	0,009^{gh}	0,014^{ab}	0,011^{b}
	Mean	0,010^{de}	0,011^{ab}	0,010^{ef}	0,009^{f}	0,012^{a}	0,010
Coated	Before	0,007^{l}	0,008^{jk}	0,013^{bc}	0,008^{h-k}	0,008^{ijk}	0,009^{c}
	After	0,011^{ef}	0,010^{fgh}	0,011^{ef}	0,012^{cd}	0,012^{cd}	0,011^{b}
	Transportation	0,012^{de}	0,014^{a}	0,011^{ef}	0,012^{de}	0,013^{abc}	0,012^{a}
	Mean	0,010^{ef}	0,011^{cd}	0,011^{a}	0,011^{bc}	0,011^{ab}	0,011
Mean	Before	0,008^{g}	0,008^{g}	0,010^{e}	0,008^{g}	0,009^{f}	0,009^{c}
	After	0,011^{de}	0,012^{bc}	0,011^{cd}	0,011^{bc}	0,012^{b}	0,011^{b}
	Transportation	0,011^{cd}	0,013^{a}	0,011^{de}	0,010^{de}	0,014^{a}	0,012^{a}
	Mean	0,010^{c}	0,011^{b}	0,011^{b}	0,010^{c}	0,012^{a}	0,011
Root Fresh Weight (g)							
Uncoated	Before	0,064^{c}	0,088^{bc}	0,101^{bc}	0,106^{bc}	0,088^{bc}	0,089
	After	0,005^{c}	0,011^{c}	0,005^{c}	0,009^{c}	0,013^{c}	0,009
	Transportation	0,049^{c}	0,050^{c}	0,029^{c}	0,042^{c}	0,051^{c}	0,044
	Mean	0,039^{b}	0,050^{b}	0,045^{b}	0,052^{b}	0,051^{b}	0,047
Coated	Before	0,228^{ab}	0,104^{bc}	0,088^{bc}	0,070^{c}	0,122^{bc}	0,122
	After	0,006^{c}	0,003^{c}	0,006^{c}	0,023^{c}	0,018^{c}	0,011
	Transportation	0,022^{c}	0,020^{c}	0,033^{c}	0,033^{c}	0,303^{a}	0,082
	Mean	0,085^{ab}	0,042^{b}	0,042^{b}	0,042^{b}	0,148^{a}	0,072
Mean	Before	0,146^{a}	0,096^{ab}	0,094^{ab}	0,088^{ab}	0,105^{ab}	0,106^{a}
	After	0,006^{b}	0,007^{b}	0,005^{b}	0,016^{b}	0,015^{b}	0,010^{c}
	Transportation	0,035^{b}	0,035^{b}	0,031^{b}	0,037^{b}	0,177^{a}	0,063^{b}
	Mean	0,062^{ab}	0,046^{b}	0,043^{b}	0,047^{b}	0,099^{a}	0,060
Root Dry Weight (g)							
Uncoated	Before	0,006^{d-g}	0,004^{f-l}	0,105^{a}	0,005^{f-k}	0,016^{b}	0,027^{a}
	After	0,004^{h-l}	0,004^{f-l}	0,002^{lm}	0,001^{m}	0,003^{i-m}	0,003^{e}
	Transportation	0,005^{f-j}	0,004^{g-l}	0,003^{j-m}	0,004^{h-m}	0,006^{def}	0,004^{d}
	Mean	0,005^{de}	0,004^{ef}	0,037^{a}	0,003^{f}	0,008^{b}	0,011
Coated	Before	0,011^{c}	0,004^{g-l}	0,005^{e-i}	0,012^{c}	0,007^{de}	0,008^{b}
	After	0,005^{e-i}	0,001^{m}	0,003^{klm}	0,004^{g-l}	0,003^{h-m}	0,003^{e}
	Transportation	0,005^{e-j}	0,006^{d-h}	0,008^{d}	0,005^{f-l}	0,006^{d-g}	0,006^{c}
	Mean	0,007^{c}	0,004^{f}	0,005^{de}	0,007^{c}	0,006^{d}	0,006
Mean	Before	0,008^{c}	0,004^{efg}	0,055^{a}	0,008^{c}	0,011^{b}	0,018^{a}
	After	0,004^{ef}	0,003^{ghi}	0,002^{i}	0,003^{hi}	0,003^{f-i}	0,003^{c}
	Transportation	0,005^{de}	0,005^{ef}	0,005^{de}	0,004^{e-h}	0,006^{d}	0,005^{b}
	Mean	0,006^{c}	0,004^{e}	0,021^{a}	0,005^{d}	0,007^{b}	0,009

[1]Means followed by the same letter are not significantly different.

Root Fresh Weight

Analysis of variance revealed that root fresh weight in alfalfa was significantly affected by the main effects of coating, storage, and cultivar, while the cultivar × coating, cultivar × storage, and cultivar × coating × storage interactions were also statistically significant. In contrast, the nonsignificant coating × storage interaction indicates that the relationship between the average effects of coating and storage was relatively limited when cultivar was not considered (Table 1). Across the overall means, seed coating increased root fresh weight from 0.047 g in uncoated seeds to 0.072 g in coated seeds, an increase of approximately 53.19%, indicating strong potential for coating to promote root biomass accumulation. However, storage had a much stronger effect. Root fresh weight decreased from 0.106 g before storage to 0.010 g after storage, representing a reduction of approximately 90.57%. After transportation, it increased to 0.063 g, indicating substantial recovery, although it remained approximately 40.57% below the pre-storage level. This pronounced variation demonstrates that root fresh biomass was highly sensitive to storage stage. Therefore, despite the overall positive effect of coating, storage-related physiological changes appeared to exert a much stronger influence on root biomass, and the recovery

observed after transportation was insufficient to fully restore the initial level of root development (Table 3).

Genotypic differences were a major determinant of variation in root fresh weight. Across the overall means, Sunter exhibited the greatest root fresh weight (0.099 g), followed by Bilensoy (0.062 g), whereas Icon (0.047 g), Blue Ace (0.046 g), and Bolton (0.043 g) showed lower and statistically similar values. However, responses to coating differed markedly among cultivars. Coating increased root fresh weight in Sunter from 0.051 to 0.148 g, corresponding to an increase of approximately 190.20%, and in Bilensoy from 0.039 to 0.085 g, representing an increase of 117.95%. In contrast, root fresh weight decreased by approximately 16.00%, 6.67%, and 19.23% in Blue Ace, Bolton, and Icon, respectively. The cultivar × storage interaction showed a similarly pronounced genotypic differentiation. Root fresh weight decreased sharply after storage in all cultivars, whereas after transportation, Sunter increased to 0.177 g and clearly differentiated from the other cultivars. This variation became even more evident in the three-way interaction, with treatment combinations ranging from 0.003 to 0.303 g. The greatest root fresh weight was recorded for coated Sunter after transportation (0.303 g), whereas the lowest value was observed for coated Blue Ace after storage (0.003 g). These findings demonstrate that the large overall increase in root biomass associated with coating should not be interpreted as a common response across all genotypes; rather, the overall mean was strongly influenced by the pronounced positive responses of Sunter and Bilensoy. Therefore, evaluating the agronomic effectiveness of coating requires considering specific cultivar × coating × storage combinations rather than relying solely on overall treatment means (Table 3).

The overall increase in root fresh weight associated with coating is consistent with previous studies indicating that appropriately designed coating systems may promote early root development and seedling biomass accumulation. Amirkhani et al. (2016, 2019) reported that coatings containing protein-based and biologically derived biostimulant components could promote seedling development, while Afzal et al. (2020) emphasized the potential of modern coating technologies to improve seedling establishment by delivering active ingredients to the seed microenvironment. Similarly, Qiu et al. (2020) demonstrated that biostimulant-containing coatings may promote germination and early seedling development in forage legumes, although coating performance depends on the formulation and plant material. This genotype dependence was particularly pronounced in the present study: coating markedly increased root fresh biomass in Sunter and Bilensoy but did not provide the same advantage in Blue Ace, Bolton, or Icon. Furthermore, the more than 90% reduction in overall root fresh weight after storage indicates that the potential benefits of coating cannot be considered independently of storage-related physiological changes and suggests that root biomass may be a sensitive indicator of changes in seed physiological quality. Within the three-way interaction, coated Sunter reached 0.303 g after transportation, by far the greatest value among the treatment combinations, demonstrating that an appropriate cultivar × coating combination may generate a particularly strong root growth response under specific conditions. Therefore, rather than adopting a uniform “coated seed” approach to improve root development in alfalfa, consider genotype-specific responses and post-storage performance jointly. In cultivars such as Sunter and Bilensoy, which exhibited particularly strong positive responses to coating, targeted optimization of coating materials and application conditions may provide a more appropriate strategy.

Root Dry Weight

Analysis of variance revealed that root dry weight in alfalfa was significantly affected by the main effects of coating, storage, and cultivar, as well as by all two-way and three-way interactions ($p < 0.01$) (Table 1). Across the overall means, root dry weight decreased from 0.011 g in uncoated seeds to 0.006 g in coated seeds, corresponding to a reduction of approximately 45.45% associated with coating. Storage had an even more pronounced effect. Root dry weight decreased from 0.018 g before storage to 0.003 g after storage, a reduction of 83.33%; although it subsequently increased to 0.005 g after transportation, it remained 72.22% below the pre-storage value. The coating × storage interaction showed that the magnitude of this reduction differed by coating status. In uncoated seeds, root dry weight decreased from 0.027 g before storage to 0.003 g after storage and 0.004 g after transportation, whereas the corresponding values for coated seeds were 0.008, 0.003, and 0.006 g, respectively. Notably, although coating reduced root dry weight across the overall means, coated seeds exhibited 50% greater root dry weight than uncoated seeds after transportation. This finding suggests that, although coating

may restrict root dry matter accumulation under initial conditions, it may reduce biomass loss or facilitate recovery during storage and transportation. Nevertheless, because the interaction effects were significant, interpret this response in the context of cultivar-specific treatment combinations rather than as a uniform protective effect of coating (Table 3).

Marked differences in root dry weight were observed among cultivars. Across the overall means, Bolton exhibited the greatest value (0.021 g) and was clearly differentiated from the other cultivars, followed by Sunter (0.007 g), Bilensoy (0.006 g), Icon (0.005 g), and Blue Ace (0.004 g). However, Bolton's superior overall mean should be interpreted cautiously because it was largely driven by the exceptionally high value of 0.105 g recorded for uncoated seeds before storage, and this performance was not maintained after storage. Indeed, within the cultivar × storage interaction, root dry weight in Bolton decreased from 0.055 g before storage to 0.002 g after storage and recovered only slightly to 0.005 g after transportation. Responses to coating were also genotype-dependent: coating increased dry matter accumulation in Bilensoy and especially in Icon, whereas Bolton and Sunter showed reductions. The three-way interaction clearly drove this variation, with treatment combinations ranging from 0.001 to 0.105 g. Uncoated Bolton had the highest root dry weight before storage (0.105 g), whereas uncoated Icon and coated Blue Ace had the lowest values after storage (0.001 g). In contrast, root dry weight in coated Bolton increased from 0.005 g before storage to 0.008 g after transportation, suggesting that coating may produce a different compensatory or potentially protective response in certain genotypes following storage and transportation. Thus, high initial root dry weight did not necessarily correspond to greater storage tolerance, and coating efficacy should be evaluated based on cultivar × coating × storage combinations rather than overall treatment means alone (Table 3).

The overall reduction in root dry weight associated with coating indicates that seed-coating technologies may affect different morphological and biomass components of the root system in different directions. Bıçakcı et al. (2018) reported that coating treatments in alfalfa could increase germination and radicle fresh weight under stress conditions while producing different responses in traits such as radicle length and dry weight. Similarly, Arslan et al. (2020) showed that environmental stress substantially affected root and shoot length, as well as fresh and dry biomass traits, in coated alfalfa seeds, indicating that coating efficacy depends on the environmental conditions under which seeds develop. Öten and Tuzlacı (2024) likewise reported treatment-dependent differences in early seedling traits, including root fresh and dry weight, following different priming and coating treatments in alfalfa. In this context, the decrease in root dry weight from 0.018 g before storage to 0.003 g after storage in the present study shows that storage was a major factor limiting root dry matter accumulation, beyond the main effect of coating. More importantly, although coating was associated with an overall reduction of 45.45%, coated seeds exhibited greater root dry weight than uncoated seeds after transportation, demonstrating that the direction and magnitude of the coating response varied across storage stages. Overall, maintaining root dry matter accumulation in alfalfa is too complex to attribute solely to coated seeds and requires consideration of the cultivar × coating × storage/transportation interaction. Therefore, post-storage biomass retention and genotype-specific responses, rather than initial performance alone, should be considered key selection criteria when optimizing seed-coating technologies for alfalfa.

CONCLUSION

This study showed that the effects of seed coating, storage, and transportation on early seedling development and biomass accumulation in alfalfa varied substantially by trait and cultivar. Seed coating increased seedling length and vegetative dry weight, indicating positive effects on shoot development and dry matter accumulation, whereas it reduced root length and root dry weight; in contrast, root fresh weight increased markedly following coating. Storage and transportation resulted in particularly pronounced changes in root-related traits, with substantial reductions in root length and root fresh and dry weight after storage, followed by partial recovery in some traits and cultivars after transportation. Conversely, the increases observed in seedling length and vegetative dry weight after storage and/or transportation indicate that coating and storage processes elicited contrasting responses among different components of seedling development. The significant cultivar × coating, cultivar × storage, and particularly three-way interactions clearly demonstrate that a uniform coating strategy is unlikely to produce equivalent responses across all alfalfa cultivars. Indeed, Icon was distinguished by greater seedling length, Sunter by root length and root fresh biomass, and Bolton by high initial root dry matter accumulation; however, the extent to which these advantages were maintained varied according to

coating and storage conditions, demonstrating that high initial performance does not necessarily confer greater storage tolerance. Overall, the effectiveness of coating technologies in commercial alfalfa seed production should be evaluated not only according to their initial effects but also according to the extent to which seedling vigor and the balance between root and shoot development are maintained throughout storage and transportation. Therefore, genotype-specific optimization of coating materials and storage protocols is an important strategy for maintaining high, balanced post-storage seedling performance and improving the commercial effectiveness of coated alfalfa seeds.

ACKNOWLEDGMENTS

This study was supported by the Scientific Research Projects Coordination Unit of Selçuk University under Project No. 25201029. This study was prepared as part of the M.Sc. thesis conducted by Muhammed Emin EROL at the Department of Field Crops, Graduate School of Natural and Applied Sciences, Selçuk University.

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KURAKLIK STRESİ ALTINDA BİYOSTİMÜLANT DESTEKLİ TOHUM PRİMİNGİNİN TARLA BİTKİLERİNDE ÇİMLENME VE ERKEN FİDE GELİŞİMİNE ETKİLERİ

EFFECTS OF BIOSTIMULANT-ASSISTED SEED PRIMING ON GERMINATION AND EARLY SEEDLING DEVELOPMENT IN FIELD CROPS UNDER DROUGHT STRESS

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Özet
Kuraklık stresi, tarla bitkilerinde tohum çimlenmesini ve erken fide gelişimini sınırlandıran başlıca abiyotik stres faktörlerinden biridir. Kurak ve yarı kurak tarım ekosistemlerinde yetersiz toprak nemi; tohumların su alımını kısıtlamakta, enzimatik aktivasyonu aksatmakta, rezerv maddelerin mobilizasyonunu geciktirmekte ve oksidatif stresi artırarak düşük çıkış oranı ile düzensiz bitki kuruluşuna yol açmaktadır. Tohum primingi, tohumların kontrollü koşullarda kısmi hidrasyona tabi tutulması ve radikula çıkışı gerçekleşmeden yeniden kurutulması esasına dayanan bir ekim öncesi uygulamadır. Biyostimülantlarla desteklenen tohum primingi ise kuraklık toleransının artırılmasında sürdürülebilir ve yenilikçi bir yaklaşım olarak öne çıkmaktadır. Bu derleme çalışmasında, biyostimülant destekli tohum priminginin tarla bitkilerinde çimlenme özellikleri, fide canlılığı ve fizyolojik tolerans mekanizmaları üzerindeki etkilerine ilişkin güncel bilimsel bulgular değerlendirilmiştir. İncelenen biyostimülantlar arasında deniz yosunu ekstraktları, humik ve fulvik asitler, amino asitler, protein hidrolizatları, kitosan, bitki gelişimini teşvik eden rizobakteriler ve mikorizal mantarlar yer almaktadır. Literatür bulguları, biyostimülant destekli priming uygulamalarının su kısıtı altında çimlenme yüzdesini ve çıkış hızını; radikula ve koleoptil uzunluğunu, kök gelişimini ve erken dönem fide biyokütlesini iyileştirebildiğini göstermektedir. Biyostimülant destekli primingin kuraklık toleransına katkısı; bağıl su içeriğinin korunması, prolin ve çözünebilir şekerler gibi ozmotik düzenleyicilerin birikiminin desteklenmesi, antioksidan enzim aktivitelerinin artırılması, reaktif oksijen türlerinin neden olduğu hasarın sınırlandırılması, hücre zarı bütünlüğünün korunması ve besin elementi alım etkinliğinin iyileştirilmesiyle ilişkilendirilmektedir. Bununla birlikte, uygulamaların etkinliği; bitki türü ve çeşidi, biyostimülantın bileşimi, dozu ve uygulama süresi, tohumun fizyolojik kalitesi, stres şiddeti ve çevresel koşullara bağlı olarak değişmektedir. Sonuç olarak biyostimülant destekli tohum primingi, iklim değişikliği koşullarında erken gelişme dönemindeki kuraklık kaynaklı kayıpları azaltmaya katkı sağlayabilecek, çevre dostu ve ekonomik bir yönetim stratejisi olarak değerlendirilebilir.
Anahtar kelimeler: Tohum primingi, biyostimülant, kuraklık stresi, çimlenme, fide gelişimi, tarla bitkileri.

Abstract
Drought stress is one of the major abiotic stress factors limiting seed germination and early seedling development in field crops. In arid and semi-arid agroecosystems, insufficient soil moisture restricts water uptake by seeds, disrupts enzymatic activity, delays the mobilization of storage reserves, and increases oxidative stress, leading to low emergence rates and uneven crop establishment. Seed priming is a pre-sowing treatment based on the partial hydration of seeds under controlled conditions, followed by redrying before radicle emergence. Biostimulant-assisted seed priming has emerged as a sustainable and innovative approach to improving drought tolerance. This review evaluates recent scientific findings on the effects of biostimulant-assisted seed priming on germination characteristics, seedling vigour, and physiological tolerance mechanisms in field crops. The biostimulants considered include seaweed extracts, humic and fulvic acids, amino acids, protein hydrolysates, chitosan, plant growth-promoting rhizobacteria, and mycorrhizal fungi. The literature indicates that biostimulant-assisted priming can improve germination percentage and emergence rate, as well as radicle and coleoptile length, root development, and early seedling biomass under water-limited conditions. The contribution of biostimulant-assisted priming to drought tolerance is associated with the maintenance of relative water

content, enhanced accumulation of osmolytes such as proline and soluble sugars, increased antioxidant enzyme activities, limitation of damage caused by reactive oxygen species, preservation of cell membrane integrity, and improved nutrient uptake efficiency. However, the effectiveness of these treatments varies depending on crop species and cultivar, biostimulant composition, application dose and duration, seed physiological quality, stress severity, and environmental conditions. In conclusion, biostimulant-assisted seed priming can be considered an environmentally friendly and cost-effective management strategy that may contribute to reducing drought-related losses during early crop development under changing climate conditions.
Keywords: Seed priming, biostimulants, drought stress, germination, seedling development, field crops.

GİRİŞ

İklim değişikliği, küresel tarımsal üretimin sürdürülebilirliğini tehdit eden başlıca çevresel sorunlardan biri hâline gelmiştir. Artan sıcaklıklar, yağış rejimlerindeki düzensizlikler ve ekstrem iklim olaylarının daha sık görülmesi, bitkisel üretimde verim düzeylerini olumsuz yönde etkileyerek önemli verim kayıplarına yol açmaktadır. IPCC raporlarında, küresel sıcaklık artışının özellikle kurak ve yarı kurak bölgelerde tarımsal üretim sistemleri üzerindeki baskıyı artıracağı, su kaynakları üzerindeki rekabeti güçlendireceği ve gıda güvenliği açısından önemli riskler oluşturacağı vurgulanmaktadır (IPCC, 2022). Bu bağlamda kuraklık, tarla bitkilerinin çimlenmeden hasada kadar tüm gelişim dönemlerini etkileyen ve verim kayıplarına neden olan en önemli abiyotik stres faktörlerinden biri olarak değerlendirilmektedir (Farooq et al., 2009; Marthandan et al., 2020).

Kurak ve yarı kurak alanların dünya tarım alanları içerisindeki yüksek payı, yağışa dayalı üretim yapan bölgelerin iklim değişikliğine karşı kırılganlığını artırmaktadır. Yağışların miktar, zaman ve dağılım bakımından düzensizleşmesi; toprak neminin kritik seviyelerin altına düşmesine, bitkilerin suya erişiminin sınırlanmasına ve özellikle erken gelişme döneminde düzensiz ve yetersiz bitki çıkışına neden olmaktadır (Singh et al., 2025; Janah et al., 2025). Türkiye'de Orta Anadolu, Güneydoğu Anadolu ve İç Ege başta olmak üzere birçok üretim bölgesinde kuraklık riski giderek daha belirgin hâle gelmektedir. Yağışlardaki azalma, yüksek sıcaklıklar ve yeraltı su kaynakları üzerindeki baskı; buğday, arpa, mısır, nohut ve yem bitkileri gibi stratejik öneme sahip tarla bitkilerinde üretim miktarını olumsuz etkilemekte ve verim düzeylerinin korunmasını güçleştirmektedir. Bu nedenle, kimyasal girdi kullanımını artırmadan bitkilerin stres toleransını destekleyebilecek çevre dostu ve uygulanabilir üretim yaklaşımlarına ihtiyaç duyulmaktadır (Yavaş et al., 2016; Ceritoğlu et al., 2021).

Bitki yaşam döngüsünde çimlenme ve erken fide gelişimi, kuraklık stresine karşı en hassas dönemler arasında yer almaktadır. Tohumun çimlenebilmesi için imbibisyonun gerçekleşmesi, enzimatik faaliyetlerin başlaması, depo maddelerinin mobilize edilmesi ve radikulanın tohum kabuğunu aşarak çıkış yapması gerekmektedir. Ancak toprak su potansiyelinin düşmesi, tohumun su alımını yavaşlatmakta, metabolik faaliyetleri sınırlandırmakta ve çimlenme oranı ile hızını azaltmaktadır (Bradford, 1986; Paparella et al., 2015).

Kuraklık koşullarında geç, düzensiz veya yetersiz bitki çıkışı; bitki sıklığının azalmasına, fide gelişiminin zayıflamasına ve sonuç olarak nihai verimin düşmesine neden olmaktadır. Buğday, mısır ve baklagil türlerinde kuraklık stresinin çimlenme, kök ve gövde gelişimi ile verim bileşenleri üzerinde önemli kayıplara yol açabildiği bildirilmektedir (Naseem ve Bano, 2014; Çığ et al., 2022). Erken dönemde ortaya çıkan düzensiz bitki çıkışı, yalnızca doğrudan verim kaybına neden olmamakta; aynı zamanda yeniden ekim gereksinimi, yabancı ot rekabetinin artması, sulama ve gübreleme uygulamalarının etkinliğinin azalması ve hasat homojenliğinin bozulması gibi ekonomik sonuçlar da doğurmaktadır. Bu nedenle, kuraklık koşullarında güçlü, düzenli ve yeterli bitki çıkışının sağlanması, üretim sistemlerinin dayanıklılığı açısından kritik önem taşımaktadır (Jatana et al., 2024). Yüksek fizyolojik kaliteye ve fide gücüne sahip tohumlar, uygun olmayan nem ve sıcaklık koşullarında daha hızlı çimlenebilmekte, daha düzenli çıkış gösterebilmekte ve erken gelişme döneminde çevresel streslere daha yüksek uyum sağlayabilmektedir (Heydecker et al., 1973; Bradford, 1986).

Bu olumsuzlukların azaltılmasında tohum primingi; tohumların ekim öncesinde kontrollü olarak nemlendirilmesi ve radikula çıkışı gerçekleşmeden yeniden kurutulması esasına dayanan, çimlenme ile erken fide gelişimini destekleyen düşük maliyetli ve çevre dostu bir ön ekim tekniği olarak öne çıkmaktadır (Bradford, 1986; Paparella et al., 2015). Tohum primingi uygulamalarının bitki gelişimini teşvik eden rizobakteriler (PGPR), fitohormonlar, ozmotik ajanlar ve doğal ekstraktlar gibi biyostimülantlarla desteklenmesi ise tohumların kuraklık stresine karşı toleransını artırma ve erken

dönem gelişimini güçlendirme açısından umut verici bir yaklaşım sunmaktadır (Mahakham et al., 2017; Marthandan et al., 2020).

Biyostimülant destekli tohum primingi uygulamalarının başarısı; bitki türü ve çeşidi, kullanılan biyostimülantın niteliği ve konsantrasyonu, priming süresi, uygulama yöntemi, kurutma koşulları ve stresin şiddeti gibi çeşitli faktörlere bağlı olarak değişebilmektedir. Bu nedenle, farklı tarla bitkilerinde elde edilen bulguların birlikte değerlendirilmesi ve uygulamaların etkinliğini belirleyen koşulların ortaya konulması önem taşımaktadır. Bu derlemenin amacı, kuraklık stresi altında biyostimülant destekli tohum primingi uygulamalarının tarla bitkilerinde çimlenme, erken fide gelişimi ve fizyolojik stres toleransı üzerindeki etkilerini güncel literatür ışığında değerlendirmektir. Bu kapsamda, başlıca tohum primingi yöntemleri ve biyostimülant grupları, uygulamaların olası etki mekanizmaları, farklı tarla bitkilerinde bildirilen sonuçlar, uygulama koşulları ve gelecekteki araştırma gereksinimleri ele alınacaktır.

MATERYAL VE YÖNTEM

Bu çalışma, tarla bitkilerinde kuraklık stresine karşı biyostimülant destekli tohum primingi uygulamalarının etkilerini, mekanizmalarını ve tarımsal çıktılarını inceleyen kapsamlı bir derleme araştırması niteliğindedir. Çalışmanın materyalini; Web of Science, Scopus, ScienceDirect, PubMed, Google Scholar ve TÜBİTAK ULAKBİM DergiPark gibi uluslararası ve ulusal akademik veri tabanlarında taranan, hakemli dergilerde yayımlanmış araştırma makaleleri, derlemeler ve resmi kurumsal raporlar oluşturmaktadır.

Literatür tarama sürecinde "seed priming", "biostimulants", "drought stress", "water deficit", "seed germination", "seedling establishment", "field crops", "PGPR", "mycorrhiza", "seaweed extract" ile bunların Türkçe karşılıkları olan "tohum primingi", "biyostimülant", "kuraklık stresi", "çimlenme", "fide gelişimi" ve "tarla bitkileri" anahtar kelimeleri kullanılmıştır. Taramada öncelikli olarak son yıllardaki güncel araştırmalar ile alandaki temel ve öncü metodolojik çalışmalara odaklanılmıştır.

Elde edilen veriler; kuraklık stresinin çimlenme ve fide fizyolojisine etkileri, tohum primingi teknikleri, biyostimülant grupları ve etki mekanizmaları, tarla bitkileri gruplarında (tahıllar, yemeklik dane baklagiller, yağ ve yem bitkileri) yürütülen somut uygulama örnekleri ile sahadaki kısıtlar ve araştırma gereksinimleri tematik başlıkları altında sentezlenmiş ve analitik bir yaklaşımla tartışılmıştır.

BULGULAR VE TARTIŞMA

Kuraklık Stresinin Çimlenme Ve Fide Gelişimine Etkileri

Kuraklık stresi, tarla bitkilerinde çimlenme ve erken fide gelişimi evrelerini doğrudan etkileyerek tohumun su alımını, enzimatik faaliyetlerini ve metabolik süreçlerini baskılayan başlıca çevresel sınırlayıcılardan biridir. Tohum çimlenmesi, fiziksel su alımıyla başlayan, metabolik hazırlıklarla devam eden ve kökçük çıkışıyla tamamlanan birbirini izleyen karmaşık biyolojik süreçlerden oluşmaktadır. Ortamda yeterli nem bulunmadığında tohumun su emilim hızı yavaşlamakta, embriyonik dokularda hücre bölünmesi ve büyümesi durmakta, dolayısıyla çimlenme süreci belirgin düzeyde gecikmektedir (Bradford, 1986; Paparella et al., 2015). Bu durum, kuraklık koşullarında tohumların çimlenme yüzdesi, çimlenme hızı ve tohum canlılık indekslerinde önemli gerilemelere neden olmakta; ortalama çimlenme süresini uzatarak tarladaki bitki çıkışını zayıflatmaktadır (Farooq et al., 2009; Kumari et al., 2026). Nitekim yapılan çalışmalarda, su kısıtının buğday, arpa, mısır, kolza ve sorgum gibi stratejik tarla bitkilerinde çimlenme performansını ve çıkış gücünü önemli ölçüde düşürdüğü bildirilmektedir (Li et al., 2020; Zhu et al., 2021; García-Cánovas et al., 2024).

Çimlenmeyi takip eden erken fide dönemi de su eksikliğine karşı oldukça hassastır. Toprak neminin yetersiz olması, genç fidelerde kök ve sürgün uzamasını sınırlandırmakta, taze ve kuru biyokütle birikimini büyük oranda azaltmaktadır. Dokuların yeterli su turgoruna ulaşamaması nedeniyle hücre genişlemesi durmakta, yaprak alanı küçülmekte, stomalar kapanmakta ve fotosentez kapasitesi zayıflayarak bitkinin erken dönemdeki büyüme ivmesi kaybolmaktadır (Begum et al., 2019; Jiménez-Arias et al., 2022). Bu süreçte kök sisteminin derinlere ve yanlara doğru yeterince gelişememesi, fidenin toprak profilindeki kısıtlı suya ve temel besin elementlerine erişim imkanını daha da daraltarak gelişme geriliğini derinleştirmektedir.

Fizyolojik gerilemelerin yanı sıra kuraklık stresi, hücresel düzeyde oksidatif dengenin bozulmasına da yol açmaktadır. Su açığı çeken bitki dokularında reaktif oksijen türlerinin kontrolsüz şekilde artması; hücresel membranların yapısını bozmakta, zar geçirgenliğini artırmakta ve doku hasarına zemin

hazırlamaktadır (Farooq et al., 2009; Marthandan et al., 2020). Nohut ve soya fasulyesi gibi baklagil türlerinde kuraklık, dokulardaki bağıl su içeriğini düşürerek hücre bütünlüğünde ciddi hasarlar oluşturmaktadır (Khan et al., 2019; Almakas et al., 2025). Her ne kadar bitkiler bu zararı sınırlandırmak amacıyla doğal koruyucu enzimlerini ve ozmotik dengeleyici maddeleri devreye sokmaya çalışsa da, kuraklığın şiddetli veya uzun süreli olması durumunda bu savunma kapasitesi yetersiz kalmaktadır. Sonuç olarak kuraklık stresi, tohum çimlenmesinden başlayarak erken fide büyümesini, bitki sıklığını ve genel tarla çıkışını doğrudan tehlikeye atan çok boyutlu bir olumsuzluk tablosu ortaya çıkarmaktadır (Jatana et al., 2024; Janah et al., 2025).

Tohum Primingi: Kavram, Amaç Ve Uygulama Yöntemleri

Tohum primingi, tohumların kontrollü koşullarda kısmi hidrasyona tabi tutulması, hücresel metabolik süreçlerin aktive edilmesi ve kökçük çıkışı gerçekleşmeden önce tohumların yeniden kurutulması esasına dayanan bir ön ekim tekniğidir (Bradford, 1986; Paparella et al., 2015). Bu uygulamanın temel amacı; çimlenme sürecinde rol oynayan enzim sistemlerini, hücresel onarım mekanizmalarını ve stres belleğini önceden harekete geçirerek tarlada daha hızlı, homojen ve çevresel streslere dirençli bir bitki çıkışı sağlamaktır. Düşük maliyetli, çevre dostu ve sahada uygulanabilir bir yaklaşım olması nedeniyle tohum primingi, kurak ve yarı kurak tarım alanlarında erken dönem risklerini azaltmada yaygın şekilde tercih edilmektedir (Ceritoğlu et al., 2021; Singh et al., 2025).

Uygulanan ajanın ve yöntemin niteliğine bağlı olarak priming teknikleri farklı gruplara ayrılmaktadır. Bunlardan en basiti olan hidropriming, tohumların saf su içerisinde belirli bir süre bekletilerek ardından kontrollü şekilde kurutulmasıdır; kimyasal kalıntı riski taşımaması ve pratik uygulanabilirliği sayesinde buğday, arpa, mısır ve baklagillerde tohum gücünü artırmada sıklıkla kullanılmaktadır (Marthandan et al., 2020). Osmopriming yönteminde ise polietilen glikol (PEG) gibi osmotik ajanlar kullanılarak su alımı sınırlandırılmakta, böylece kökçük çıkışı engellenirken tohumun metabolik hazırlığı tamamlanmaktadır (Paparella et al., 2015; Jatana et al., 2024). Halopriming uygulamalarında potasyum, kalsiyum veya sodyum tuz çözeltilerinden yararlanılarak tohumda hafif bir stres uyarımı oluşturulmakta ve bu sayede kuraklığa karşı çapraz tolerans geliştirilmektedir (Zhu et al., 2021).

Hormonal priming kapsamında giberellik asit, salisilik asit ve melatonin gibi düzenleyicilerin kullanımı; çimlenme enzimlerinin uyarılması, savunma mekanizmalarının güçlendirilmesi ve hücresel zar bütünlüğünün korunması yoluyla kuraklık kaynaklı kayıpları önemli ölçüde sınırlandırmaktadır (Kumari et al., 2026). Son yıllarda biyolojik yaklaşımların önem kazanmasıyla öne çıkan biyopriming tekniğinde ise tohumlar bitki gelişimini teşvik eden rizobakteriler (PGPR) veya mikorizal mantar türleriyle aşılanmaktadır (Harsonowati et al., 2026). Tohum yüzeyinde ve kök bölgesinde kolonize olan bu yararlı mikroorganizmalar, biyofilm matrisi oluşturarak su tutulmasını kolaylaştırmakta ve fidenin besin alımını desteklemektedir (Naseem ve Bano, 2014; Ansari et al., 2021). Benzer şekilde yeni nesil bir yaklaşım olan nanopriming uygulamaları da uygun dozlardaki nanopartiküller vasıtasıyla tohum içi metabolik süreçleri uyararak kuraklık direncini artırmayı hedeflemektedir (Jatana et al., 2024). Farklı mekanizmalar üzerinden işleyen bu yöntemler, kuraklık koşullarında tohumların fizyolojik performansını ve fide çıkış gücünü güvence altına almayı amaçlamaktadır.

Biyostimülant Kavramı ve Başlıca Biyostimülant Grupları

Biyostimülantlar, doğrudan bir besin maddesi sağlama amacı gütmeksizin, düşük dozlarda uygulandıklarında bitkilerin besin elementi kullanım etkinliğini artıran, abiyotik stres koşullarına tolerans kazandıran ve ürün kalitesini destekleyen doğal kökenli maddeler veya yararlı mikroorganizmalardır (Rouphael ve Colla, 2020). Avrupa Birliği gübre mevzuatında yasal bir çerçeveye kavuşturulan bu girdiler; humik maddelerden mikrobiyal inokulantlara kadar oldukça geniş bir yelpazeyi içine almaktadır (López-Serrano et al., 2026). Türkiye'de de özellikle 2000'li yıllardan itibaren bitki aktivatörleri ve mikrobiyal preparatlar kapsamında yaygınlaşan biyostimülantlar, kimyasal girdi bağımlılığını azaltan çevre dostu ve sürdürülebilir tarımsal üretim sistemlerinin önemli bir bileşeni durumuna gelmiştir (Külahtaş ve Çokuysal, 2016; Baran ve Erbaş Köse, 2022). Tohum primingi uygulamalarında kullanılan biyostimülantlar, kaynaklarına ve etki biçimlerine göre başlıca birkaç grupta toplanmaktadır.

Deniz yosunu ekstraktları (özellikle *Ascophyllum nodosum* ve *Ecklonia maxima*), bünyelerinde barındırdıkları doğal büyüme düzenleyiciler, betain, mannitol ve iz elementler sayesinde tohum çimlenmesini uyarmakta, kök gelişimini teşvik etmekte ve erken dönem su kısıtına karşı fizyolojik

koruma sağlamaktadır (Ma et al., 2022; López-Serrano et al., 2026). Leonardit veya organik kaynaklardan elde edilen humik ve fulvik asitler, tohum ve kök çevresinde katyon değişimini ile su tutma kapasitesini iyileştirerek fidenin su ve besin alımını kolaylaştırmaktadır. Amino asitler ve protein hidrolizatları ise hücresel düzeyde ozmotik dengenin korunmasına, antioksidan sistemlerin desteklenmesine ve kuraklık baskısı altındaki fidelerde metabolik dengenin sürdürülmesine katkıda bulunmaktadır (Rouphael ve Colla, 2020). Ayrıca çeşitli bitkisel özütler ile doğal bir biyopolimer olan kitosan; hücre zarı bütünlüğünü koruyarak ve savunma tepkilerini uyararak tohumların çimlenme gücünü desteklemektedir (Jatana et al., 2024; Wazeer et al., 2025).

Mikrobiyal biyostimülantlar grubunda yer alan bitki gelişimini teşvik eden rizobakteriler (PGPR) ve arbüsküler mikorizal mantarlar (AMF), tohum priminginde etkinliği sıklıkla araştırılan unsurlar arasındadır. *Bacillus*, *Pseudomonas* ve *Azospirillum* gibi yararlı bakteri cinsleri; büyüme düzenleyici maddelerin üretimi, fosfatın yarayışlı hâle getirilmesi ve salgıladıkları biyofilm matrisi sayesinde tohum çevresinde nem koruyucu mikro alanlar oluşturarak kuraklığın yıkıcı etkilerini hafifletmektedir (Naseem ve Bano, 2014; Ansari et al., 2021; Harsonowati et al., 2026). Mikorizal mantarlar ise kök yüzey alanını ve emilim kapasitesini belirgin biçimde artırarak bitkinin kısıtlı toprak nemine ve fosfor başta olmak üzere temel besin elementlerine ulaşmasını güvence altına almaktadır (Begum et al., 2019; Chandrasekaran, 2022). Bunların yanı sıra vermikompost özütleri ve poliaminler gibi organik kökenli diğer bileşikler de tohumların çimlenme enerjisini ve erken fide dayanıklılığını pekiştiren tamamlayıcı biyostimülant kaynakları olarak öne çıkmaktadır.

Tarla Bitkilerinde Uygulama Örnekleri

Biyostimülant destekli tohum primingi uygulamaları, kuraklık stresi altındaki tarla bitkilerinde çimlenme performansını ve erken fide gelişimini iyileştirmede geniş bir kullanım alanı bulmaktadır. Farklı bitki gruplarında yürütülen araştırmalar, bu uygulamaların türe ve genotipe özgü olumlu fizyolojik tepkiler ortaya çıkardığını göstermektedir. Tahıllar arasında özellikle buğday (*Triticum aestivum* L.), biyostimülant ve mikrobiyal tohum uygulamalarının en yoğun araştırıldığı türlerden biridir. Buğday tohumlarına uygulanan yararlı bakteri inokulasyonlarının kısıtlı toprak nemi koşullarında bitki gelişimini desteklediği, PEG ile simüle edilen kuraklık ortamında fide taze ağırlığı ile kök uzunluğunu artırdığı ve hücre zarı hasarını azalttığı belirlenmiştir (Li et al., 2020; Çığ et al., 2022). Benzer şekilde *Streptomyces* ve *Pseudomonas* suşları ile ekzopolisakkarit üreten rizobakterilerin salisilik asit gibi elisitörlerle birlikte uygulanması; buğdayda fotosentetik verimliliği, çözünür şeker ve protein birikimini koruyarak su açığı kaynaklı hasarları hafifletmiştir (Khan ve Bano, 2019; Ansari et al., 2021). Diğer serin iklim tahılı olan arpa (*Hordeum vulgare* L.) tohumlarında ise düşük dozda melatonin, osmotik ajanlar ve hidropriming uygulamalarının ortalama çimlenme süresini kısalttığı ve suboptimal nem şartlarında erken fide çıkış gücünü belirgin biçimde artırdığı bildirilmektedir (García-Cánovas et al., 2024; Janah et al., 2025).

Sıcak iklim tahıllarından mısırda (*Zea mays* L.), su stresi koşullarında biyostimülant destekli uygulamalar tohumun su alımını hızlandırmakta ve solmayı geciktirmektedir. Mısır tohumlarının giberellik asit ve melatonin ile muamele edilmesi, kuraklık altında çimlenme oranını %90'ın üzerine çıkarırken fide boyunu ve kök gelişimini desteklemiştir (Kumari et al., 2026). Ayrıca ekzopolisakkarit üreten PGPR suşları ve doğal bitki özütleri ile yapılan tohum uygulamalarının, mısır fidelerinde bağıl su içeriğini koruduğu ve kısıtlı sulama şartlarında erken dönem biyokütle kaybını önlediği saptanmıştır (Naseem ve Bano, 2014; Melo et al., 2026). Yağ bitkileri grubunda ayçiçeği (*Helianthus annuus* L.) tohumlarında hidropriming, osmopriming ve mikrobiyal destekli uygulamalar; çimlenme homojenliğini artırmakta, kök mimarisini güçlendirerek fidenin su kullanım etkinliğine katkı sağlamakta ve kuraklık stresine karşı çapraz tolerans oluşturmaktadır (Ceritoğlu et al., 2021; López-Serrano et al., 2026).

Yemeklik dane baklagiller ve endüstri bitkilerinde de biyostimülant destekli tohum primingi kritik avantajlar sağlamaktadır. Nohut (*Cicer arietinum* L.), mercimek ve fasulye tohumlarında *Bacillus* tabanlı mikrobiyal inokulasyonlar ile büyüme düzenleyicilerin birlikte kullanımı, kuraklık altında dokulardaki bağıl su içeriğini yükseltmiş, hücre zarı geçirgenliğini ve lipit peroksidasyonunu sınırlandırmıştır (Khan et al., 2019). Baklagillerde tohum primingi aynı zamanda nodülasyon ve biyolojik azot fiksasyonu süreçlerine de erken dönemde ivme kazandırmaktadır (Harsonowati et al., 2026). Soya fasulyesinde (*Glycine max* L.) doğal biyopolimer matrisleri ve yararlı mikroorganizmalarla yapılan tohum primingi işlemleri, kuraklık stresinde çimlenme hızını artırmış ve antioksidan enzim aktivitelerini uyararak fide canlılığını korumuştur (Almakas et al., 2025). Fiğ başta olmak üzere yem

bitkilerinde ise mikoriza (AMF) ve PGPR içeren mikrobiyal formülasyonlar, kök yüzey alanını ve besin yarayışlılığını artırarak erken dönemdeki su kısıtının hafifletilmesine ve tarla çıkışının desteklenmesine katkı sağlamaktadır (Begum et al., 2019; Baran ve Erbaş Köse, 2022).

Uygulamalara İlişkin Kısıtlar Ve Araştırma Gereksinimleri

Biyostimülant destekli tohum primingi uygulamaları tarla bitkilerinde kuraklık stresine karşı önemli kazanımlar sağlasa da yöntemin pratik tarımsal üretime aktarılmasında ve geniş alanlarda yaygınlaştırılmasında bazı temel kısıtlar ile araştırma gereksinimleri bulunmaktadır. Bu güçlüklerin başında, uygulanan yöntemlerin bitki türü ve genotipine bağlı olarak yüksek değişkenlik göstermesi gelmektedir. Aynı biyostimülant kaynağı veya priming süresi bir çeşitte çimlenme performansını ve erken fide canlılığını belirgin düzeyde teşvik ederken, farklı bir genotipte sınırlı kalabilmekte ya da tamamen etkisiz olabilmektedir (Khan ve Bano, 2019; Wazeer et al., 2025). Bu durum, uygulamaların genelleştirilmesini güçleştirmekte ve her bitki grubu için optimize edilmiş çeşide özgü uygulama protokollerinin geliştirilmesini zorunlu kılmaktadır.

Bir diğer önemli kısıt, biyostimülant konsantrasyonlarının ve uygulama sürelerinin standardize edilememesidir. Literatürde rapor edilen dozlar ve muamele süreleri oldukça geniş bir aralığa yayılmakta; optimum eşik değerinin altındaki konsantrasyonlar stres toleransını yeterince tetikleyemezken, aşırı dozlar fitotoksik etki oluşturabilmekte veya tohumun aşırı hidrasyonuna yol açarak kurutma sırasında embriyo hasarı riski yaratabilmektedir (García-Cánovas et al., 2024; Singh et al., 2025). Bunun yanı sıra, laboratuvar ve iklim odası koşullarında polietilen glikol (PEG) gibi kimyasal ajanlarla simüle edilen kuraklık denemelerinde elde edilen başarılı sonuçlar, tarla koşullarında her zaman aynı düzeyde sergilenememektedir. Sahadaki değişken toprak pH'sı, organik madde düzeyi, yerli toprak mikrobiyotasıyla rekabet ve öngörülemeyen iklim dinamikleri biyostimülantların etkinliğini doğrudan değiştirebilmektedir (Melo et al., 2026; López-Serrano et al., 2026). Bu nedenle kontrollü ortamlarda elde edilen verilerin çok lokasyonlu tarla denemeleriyle doğrulanması gerekmektedir.

Özellikle mikrobiyal kökenli biyostimülantlarda raf ömrü, formülasyon teknolojisi ve tohum yüzeyindeki bakteri ya da mantar canlılığının korunması önemli bir lojistik engel teşkil etmektedir (Harsonowati et al., 2026). Diğer taraftan priming işleminden geçmiş tohumların metabolik olarak yarı aktif durumda bulunması, bu tohumların depolama ömrünü kısaltmakta ve uzun süreli saklama şartlarında çimlenme gücünün hızla kaybolmasına neden olabilmektedir (Ceritoğlu et al., 2021). Son olarak, uygulamaların çiftçi ölçeğindeki maliyet-etkinliğini gösteren ekonomik analizlerin yetersizliği, yerel biyostimülantların tescil ve mevzuat süreçleri ile üretici düzeyindeki eğitim eksiklikleri yöntemin yaygınlaşmasını engellemektedir (Külahtaş ve Çokuysal, 2016). Bu araştırma gereksinimlerinin karşılanması ve mevcut kısıtların giderilmesi, biyostimülant destekli tohum priminginin sürdürülebilir tarımda güvenilir bir girdi olarak yer edinmesi açısından büyük önem taşımaktadır.

SONUÇ

Küresel iklim değişikliği ve artan kuraklık baskısı, tarla bitkileri yetiştiriciliğinde tohum çimlenmesi ve erken fide gelişimi evrelerini giderek daha riskli hâle getirmektedir. Bu derleme kapsamında incelenen güncel bilimsel bulgular; biyostimülant destekli tohum priminginin su kısıtı altında çimlenme yüzdesi, çıkış hızı, kök mimarisi ve erken dönem fide biyokütlesi üzerinde belirgin iyileşmeler sağladığını ortaya koymaktadır. Deniz yosunları, humik maddeler, amino asitler, kitosan, PGPR ve mikorizal mantarlar gibi biyostimülantların tohum primingine entegre edilmesi; dokularda bağıl su içeriğinin korunması, ozmotik dengeleyicilerin birikimi, antioksidan savunma mekanizmalarının uyarılması ve hücresel zar hasarlarının sınırlandırılması yoluyla bitkilerin kuraklık toleransını çok yönlü olarak güçlendirmektedir. Bu durum, özellikle kurak ve yarı kurak ekolojilerde yetersiz ve düzensiz tarla çıkışından kaynaklanan verim kayıplarının azaltılmasında yöntemi umut verici, çevreyle uyumlu ve sürdürülebilir bir ön ekim teknolojisi konumuna taşımaktadır.

Bununla birlikte, yöntemin sağladığı potansiyelin sahada kalıcı bir başarıya dönüşebilmesi için bazı temel uygulama kısıtlarının aşılması gerekmektedir. Biyostimülant etkinliğinin bitki tür ve genotipine göre belirgin farklılık göstermesi, standart bir uygulama yerine çeşide özgü optimum doz ve süre reçetelerinin belirlenmesini zorunlu kılmaktadır. Ayrıca laboratuvar ortamlarında elde edilen olumlu bulguların farklı toprak özellikleri ve değişken iklim koşullarını barındıran çok lokasyonlu tarla denemeleriyle teyit edilmesi, mikrobiyal formülasyonların tohum üzerindeki canlılık ve raf ömrünün uzatılması büyük önem taşımaktadır. Sonuç olarak, optimize edilmiş protokoller, geliştirilmiş

tohumculuk mevzuatı ve çiftçi düzeyinde yayım çalışmalarıyla desteklendiğinde biyostimülant destekli tohum primingi; su kısıtı altındaki tarla tarımında bitki çıkış güvencesini artıracak, sentetik girdi bağımlılığını azaltacak ve sürdürülebilir ürün güvenliğine kayda değer katkılar sunacaktır.

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KAPARİ (CAPPARİS SPİNOSA L.): BOTANİK ÖZELLİKLERİ, FİTOKİMYASAL İÇERİĞİ, FARMAKOLOJİK ETKİLERİ VE ARI MERASI OLARAK KULLANILMA POTANSİYELİ

CAPER (CAPPARIS SPINOSA L.): BOTANICAL CHARACTERISTICS, PHYTOCHEMICAL COMPOSITION, PHARMACOLOGICAL EFFECTS, AND POTENTIAL FOR USE AS A BEE PASTURE

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ÖZET
Kapari (*Capparis spinosa* L.), Capparaceae familyasına ait, başta Akdeniz Havzası olmak üzere kurak ve yarı kurak bölgelerde doğal olarak yetişen çok yıllık, dikenli bir çalı türüdür. Gıda ve geleneksel tıp alanlarında uzun süredir kullanılan bitki, son yıllarda fitokimyasal ve farmakolojik araştırmalara da konusu olmuştur. Kök, gövde, yaprak, çiçek tomurcuğu ve meyve gibi farklı organlarda flavonoitler, alkaloitler, glukosinolatlar, fenolik asitler, yağ asitleri ve steroller başta olmak üzere çeşitli biyoaktif barındırmaktadır. Literatür çalışmalarında kapari ekstrelerinin antioksidan, antidiyabetik, anti-inflamatuar, immünomodülatör, antimikrobiyal ve antikanser dâhil çeşitli biyolojik aktiviteler göstermektedir. Türkiye'de *Capparis* cinsinin *C. spinosa* ve *C. ovata* ile temsil edildiği, kaparinin kurak ve yarı kurak koşullara uyumu nedeniyle gıda, tarım ve arazi rehabilitasyonu bakımından ekonomik potansiyel taşımaktadır. Bu derlemede *C. spinosa'nın* botanik özellikleri, taksonomisi, coğrafi yayılışı, fitokimyasal ve besinsel özellikleri, farmakolojik aktiviteleri, geleneksel kullanımları, gıda işleme ve ekonomik önemi ile güvenlik profili literatür çerçevesinde ele alınmıştır. Ayrıca, çiçeklenme dönemi, nektar ve polen özellikleri, tozlaşma ilişkileri ve Türkiye'deki arı bitkisi çalışmaları dikkate alınarak *C. spinosa'nın* arı merası olarak değerlendirilme potansiyeli değerlendirilmiştir.
Anahtar Kelimeler *Capparis spinosa*; kapari; nektar; polen; arı merası; etnobotanik

ABSTRACT
Caper (*Capparis spinosa* L.), belonging to the *Capparaceae* family, is a perennial, spiny shrub species that grows naturally in arid and semi-arid regions, primarily in the Mediterranean Basin. Long used in food and traditional medicine, the plant has also become the subject of phytochemical and pharmacological research in recent years. It contains various bioactive compounds, mainly flavonoids, alkaloids, glucosinolates, phenolic acids, fatty acids, and sterols, in different organs such as roots, stems, leaves, flower buds, and fruits. Literature studies indicate that caper extracts exhibit various biological activities, including antioxidant, antidiabetic, anti-inflammatory, immunomodulatory, antimicrobial, and anticancer. Given that the genus *Capparis* is represented in Turkey by *C. spinosa* and *C. ovata*, caper holds economic potential in terms of food, agriculture, and land rehabilitation due to its adaptation to arid and semi-arid conditions. In this review, the botanical characteristics, taxonomy, geographical distribution, phytochemical and nutritional properties, pharmacological activities, traditional uses, food processing, economic importance, and safety profile of *C. spinosa* are discussed within the framework of the literature. Furthermore, considering the flowering period, nectar and pollen characteristics, pollination relationships, and bee flora studies in Turkey, the potential of *C. spinosa* to be evaluated as a bee pasture was assessed.
Keywords: *Capparis spinosa*; caper; nectar; pollen; bee pasture; ethnobotany.

GİRİŞ
Tıbbi bitkiler, insanlık tarihi boyunca en önemli tedavi kaynaklarından biri olarak kabul edilmiştir. Son yıllarda, düşük yan etki profiliyle birlikte farklı sağlık yararları sunmaları nedeniyle yenilebilir tıbbi bitkilerin sağlık üzerindeki etkilerine yönelik ilgi belirgin biçimde artmıştır (Nabavi vd., 2016). Bu bitkiler arasında *Capparis* L. cinsi, Capparaceae familyası içinde 250 ile 400 arasında değişen sayıda türü barındıran, Afrika, Asya, Akdeniz ve Amerika kıtalarının tropik ve subtropik bölgelerinde yaygın olarak bulunan bir bitki grubudur (Alsharif ve Boylan, 2025). Cins içerisinde en fazla bilinen ve ekonomik öneme sahip tür olan *Capparis spinosa* L., yaygın adıyla kapari, gıda ve geleneksel tıp alanında binlerce yıldır kullanılmaktadır. Arkeolojik kazılarda; Irak'ın Tell es-Sawwan yerleşiminde

(MÖ 5800) ve Çin'in Turpan bölgesindeki Yanghai mezarlarında (MÖ 2800) kapari tohumlarına rastlanmış olması, bitkinin insanlık tarihindeki köklü kullanımının bir kanıtı olarak değerlendirilmektedir (Chedraoui vd., 2017). Antik dönemde Dioskorides'in De Materia Medica adlı eserinde bitkinin "κάππαρις" adıyla anıldığı ve kendine özgü bir bitki olarak tanımlandığı bildirilmektedir (Christodoulou vd., 2022). Günümüzde kapari üzerine yapılan bilimsel çalışmalar; bitkinin zengin fitokimyasal içeriğini, çok yönlü farmakolojik etkilerini, geleneksel tıptaki kullanım alanlarını ve tarımsal-ekonomik potansiyelini ortaya koymaktadır.
Bu derlemenin amacı, bilimsel literatürden yararlanarak *Capparis spinosa* L.'nin botanik özellikleri, taksonomik durumu, coğrafi yayılışı (Türkiye'deki durumu dâhil), fitokimyasal bileşimi, besinsel özellikleri, farmakolojik aktiviteleri, geleneksel kullanım alanları, gıda işleme, tarımsal-ekonomik önemi, güvenlik profilini, türün çiçeklenme ve tozlaşma özellikleri ile mevcut arıcılık literatürü doğrultusunda arı merası olarak kullanılma potansiyelini ortaya koymaktır.

MATERYAL ve YÖNTEM

Bu çalışma; kaparinin botanik özellikleri, taksonomisi, coğrafi yayılışı, Türkiye'deki durumu, fitokimyasal içeriği, besinsel değeri, farmakolojik aktiviteleri, geleneksel tıpta kullanımı, gıda olarak önemi, tarımsal önemi, ekonomik önemi, arıcılık açısından önemi ve arı merası potansiyeli literatüre dayalı olarak incelenmiştir. Kaparinin incelenen özelikleri internet kaynakları ve veri tabanlarından yararlanılarak değerlendirilmiştir.
Bu çalışma; ilgili kaynakların taranması, kaynakların çeşitli açılardan değerlendirilmesi, yorumlanması ile kaparinin arıcılık için önemi ve arı merası olarak değerlendirilme potansiyelini ortaya koymaya odaklanmıştır.

Botanik Özellikleri ve Taksonomisi

Capparis spinosa L., kışın yapraklarını döken, çok yıllık bir çalı türüdür. Bitki dik, yarı yatık (precumbent) veya sarkık (pendulous) büyüme formunda gelişmektedir. Gövde dallanmamış ya da yoğun dallanmış biçimde, yeşil, kırmızı veya sarı renkte olup 4 metreye kadar uzayabilmektedir. Sürgünler kıvrımlı ya da düz, tüylü ya da tüysüz olabilmektedir (Chedraoui vd., 2017). Yapraklar oval-yuvarlak, etli yapıda olup, yaprak kulakçıkları (stipula) çoğunlukla dikene dönüşmüştür. Bitkinin *spinosa* (dikenli) adını almasının nedeni de budur (Alsharif ve Boylan, 2025).
Bitkinin yaşam döngüsü Akdeniz'de yaklaşık altı ay olup, mayıs ayında toprak yüzeyine yakın gelişen yeşil sürgünlerin oluşumuyla başlamaktadır. Çiçek tomurcukları sürgünler üzerinde; büyük, beyazdan pembemsi beyaza değişen renkte ve alacakaranlıkta açılıp gün doğumundan kısa süre sonra turgorunu kaybetmektedir (Christodoulou vd., 2022). Bu hızlı büyüme derin, geniş ve iletken bir kök sistemi gerektirmektedir. Bitkinin bu kök yapısı kayalık yarıklara, taşlık yamaçlara, eski duvarlara ve arkeolojik alanlara tutunabilmesini sağlayan karakteristik özelliklerinden biridir (Christodoulou vd., 2022; Annaz vd., 2022). Meyve, olgunlaştığında çatlayan, karpuzcuk biçiminde etli bir kapsül olup çok sayıda tohum içermektedir. Ayrıca tohumların yayılmasında karıncaların rolü olduğu bildirilmektedir (Yeğenoğlu ve Uz, 2011). *Capparis* cinsi, Capparaceae familyası içinde yer almakta ve ilk kez Carolus Linnaeus tarafından 1753 yılında Species Plantarum adlı eserde tanımlanmıştır (Chedraoui vd., 2017). *C. spinosa* grubunun morfolojik olarak yüksek değişkenlik göstermesi, tür ve alt tür düzeyinde taksonomik yorum farklılıklarına yol açmıştır. Fici (2014) tarafından Akdeniz'den Orta Asya'ya uzanan coğrafyada gerçekleştirilen taksonomik çalışmada, *C. spinosa* grubu içerisinde bir tür ve iki alt tür tanımlanmıştır (*C. spinosa* subsp. *spinosa* ve *C. spinosa* subsp. *rupestris*.).
Morfolojik yaklaşımların yalnızca nitel ve nicel vejetatif karakterlere dayanması, taksonun yanlış tanımlanmasına ve farklı varyetelerin hatalı sınıflandırılmasına neden olmuştur. Bu nedenle, moleküler verilerle desteklenen çalışmalar (örneğin AFLP – Amplified Fragment Length Polymorphism analizleri), morfolojik sınıflandırmaları tamamlayarak filogenetik ilişkilerin, farklı eko/biyotiplerin ve türün evrimsel eğilimlerinin aydınlatılmasına katkı sağlamıştır (Chedraoui vd., 2017).

Coğrafi Yayılışı ve Türkiye'deki Durumu

Capparis spinosa L., başta Güney Avrupa, Kuzey Afrika, Arap Yarımadası, Orta Doğu, Güneybatı ve Orta Asya olmak üzere geniş bir coğrafyada doğal olarak yayılış göstermektedir. Yayılış alanı doğuya doğru Çin, Nepal ve Hindistan'a, güneye doğru ise Madagaskar'a kadar uzanmaktadır (Alsharif ve Boylan, 2025; Sun vd., 2023). Bitki yükseltisi 3000 metreye kadar çıkan kayalık, kalkerli ve taşlık

arazilerde, eski duvarlarda ve yarı kurak habitatlarda kendiliğinden yetişebilmektedir. Dünya genelinde başlıca üretim alanları arasında Fas, İber Yarımadası'nın güneydoğusu, Türkiye ve İtalya'nın Pantelleria ile Salina adaları yer almaktadır. Türkiye'de *Capparis* cinsine ait doğal olarak yayılış gösteren iki tür bulunmaktadır: *Capparis spinosa* L. ve *Capparis ovata* Desf. (Bazı kaynaklarda *Capparis sicula* subsp. herbacea olarak da adlandırılmaktadır). Her iki türün de üçer varyetesi tanımlanmıştır (Yeğenoğlu ve Uz, 2011). Genel eğilim olarak *C. spinosa* varyeteleri ülkemizin batı ve güney kıyı bölgelerinde, *C. ovata* varyeteleri ise iç kesimlerde özellikle Doğu ve Güneydoğu Anadolu bölgelerinde doğal yayılış göstermektedir. *C. spinosa* çoğunlukla 300 metre rakıma kadar olan kıyı şeridinde bulunurken, *C. ovata* (*C. sicula* subsp. herbacea) daha karasal iklimin hâkim olduğu iç bölgelerde 1500-1800 metre rakıma kadar yayılış gösterebilmektedir. Türkiye'de *Capparis* türlerinin geniş bir coğrafyada doğal olarak bulunduğu bildirilmektedir. Derin ve yayılıcı kök sistemi nedeniyle kapari, erozyon kontrolü ve kurak veya ekonomik değeri düşük arazilerin değerlendirilmesi açısından da alternatif bir bitki olarak ele alınmaktadır.

Fitokimyasal İçeriği

Bitkinin kimyasal bileşimi; genotip, hasat zamanı, bitki organının büyüklüğü, çevresel koşullar ve muhafaza yöntemleri gibi çok sayıda faktöre bağlı olarak belirgin biçimde değişkenlik göstermektedir (Alsharif ve Boylan, 2025; Mohaddab vd., 2024). Başlıca fitokimyasal sınıflar; alkaloitler, flavonoitler, yağ asitleri, glukosinolatlar ve sterollerdir. Azotlu bileşikler grubunda yer alan alkaloitler, kaparinin özellikle kök kısmında yoğun biçimde bulunmakla birlikte diğer organlarda da tespit edilmiştir. Meyvelerden izole edilen kapparisin A, B ve C gibi alkaloitlerin yanı sıra stachydrine türevi bileşikler de tanımlanmıştır (Alsharif ve Boylan, 2025). Kapari, özellikle rutin, kersetin (quercetin) ve kaempferol glikozitleri başta olmak üzere yüksek düzeyde antioksidan flavonoitler içermektedir. Bu bileşikler meyve, yaprak ve tomurcuklarda değişen oranlarda bulunmakta olup, genellikle yapraklarda en yüksek konsantrasyonda tespit edilen flavonoitler öne çıkmaktadır (Mohaddab vd., 2024; Annaz vd., 2022). Kapari tohumları başta glukokapperin olmak üzere glukosinolat bileşikleri açısından zengin bir kaynaktır. Bu bileşiklerin enzimatik parçalanması sonucu oluşan metil izotiyosiyanat gibi ürünler bitkiye kendine özgü keskin kokuyu kazandırmakta ve aynı zamanda antimikrobiyal aktiviteye katkı sağlamaktadır (Annaz vd., 2022; Kdimy vd., 2022). Kapari tohum ve meyvelerinde oleik ve linoleik asit gibi doymamış yağ asitlerinin yanı sıra β-sitosterol gibi steroller ve tokoferoller tespit edilmiştir. Ayrıca bitkide karotenoitler (özellikle lutein), C vitamini ve çeşitli mineral maddeler de önemli miktarlarda bulunmaktadır (Annaz vd., 2022; Sun vd., 2023).

Besinsel Değeri

Kapari temel besin bileşenleri açısından da dikkat çekici bir potansiyele sahiptir. Meyvenin yüksek oranda nem, düşük oranda kül, orta düzeyde protein, düşük oranda yağ, kalsiyum, magnezyum, potasyum, sodyum, demir ve fosfor gibi önemli maddeleri barındırmaktadır. Mineral içeriği yetiştiricilik işlemleri, hasat zamanı ve meyve büyüklüğüne bağlı olarak değişkenlik göstermektedir (Sun vd., 2023; Annaz vd., 2022). Kapari meyvelerinin (kaper) karbonhidrat, diyet lifi, protein ve yağ içeriğinin yanı sıra orta düzeyde C vitamini taşıdığı bildirilmektedir (Mohaddab vd., 2024). Yaprak, tomurcuk ve çiçeklerde yapılan analizlerde yüksek düzeyde toplam karotenoit tespit edilmiş olup lutein baskın karotenoit bileşeni olarak öne çıkmaktadır. Tomurcuk ve çiçeklerde ise hem alfa- hem de gama-tokoferol formlarının önemli düzeylerde bulunduğu bildirilmiştir (Annaz vd., 2022). Bitki ayrıca K vitamini, bakır, E vitamini, magnezyum ve demir gibi diğer vitamin ve mineralleri de içermektedir (Annaz vd., 2022). Bu zengin besinsel profil, kaparinin yalnızca bir baharat/lezzet vericisi olarak değil, aynı zamanda çok yönlü bir gıda olarak da değerlendirilmesine olanak tanımaktadır.

Farmakolojik Aktiviteleri

Capparis spinosa L. ekstrelerinde antioksidan, antidiyabetik, anti-inflamatuar, immünomodülatör, antimikrobiyal, antikanser ve çeşitli diğer biyolojik aktivitelerinin incelendiği bildirilmektedir (Vahid vd., 2017; Nabavi vd., 2016). Kaparinin antioksidan etkisi, DPPH, FRAP ve ABTS gibi farklı testler ile değerlendirilmiş ve bu etkinin bitkideki toplam fenolik ve flavonoit içeriğiyle yakından ilişkili olduğu gösterilmiştir. Metanolik ekstrelerin, sulu ekstrelere kıyasla daha yüksek toplam fenol, flavonoit, alkaloit ve C vitamini içeriğine sahip olduğu ve buna paralel olarak daha güçlü antioksidan aktivite sergilediği bildirilmiştir (AlMousa vd., 2022). Yaprak ve kök ekstrelerinden LC-MS/MS ile karakterize

edilen rutin, resveratrol ve astragalin gibi bileşiklerin, DPPH, FRAP, ABTS ve CUPRAC test sistemlerinde belirgin radikal süpürücü aktivite göstermiştir. Kapari, geleneksel olarak başta İran olmak üzere birçok ülkede kan şekerini düşürücü bir bitki olarak kullanılmaktadır (Vahid vd., 2017). Streptozotosin ile diyabet oluşturulan fare deneylerinde kaparinin sulu ekstresinin; endojen glukoz üretimini azaltarak ve insülin duyarlılığını artırarak belirgin bir hipoglisemik etki gösterdiği ortaya konmuştur (Vahid vd., 2017). Önerilen antihiperglisemik mekanizmalar arasında ince bağırsaktan karbonhidrat emiliminin azaltılması, karaciğerde glukoneogenezin baskılanması, dokularda glukoz alımının artırılması ve beta hücrelerinin korunması/rejenerasyonu yer almaktadır (Vahid vd., 2017). Tip 2 diyabet hastalarında yürütülen çalışmada; kapari ekstresi takviyesinin metabolik parametreler üzerinde olumlu etkiler oluşturduğu bildirilmiştir (Vahid vd., 2019). Kaparinin içerdiği kersetin ve kaempferol gibi flavonoitlerin insülin duyarlılığını artırarak kan glukoz düzeyini düşürücü etki gösterdiği de ayrıca vurgulanmaktadır (Al-Raish vd., 2025). Kaparinin sulu ve metanolik ekstrelerinin; ödemi, immün hücre infiltrasyonunu ve çeşitli inflamatuar belirteçleri azaltarak anti-inflamatuar etki gösterdiği bildirilmiştir (Alsharif ve Boylan, 2025). Kapari yağının siklooksijenaz (COX-1 ve COX-2) enzimleri üzerinde; inhibitör etki gösterdiği, kapari ekstresinin belirli sitokinlerin gen ifadesini düzenleyerek genel olarak anti-inflamatuar bir bağışıklık oluşturduğu bildirilmiştir (Annaz vd., 2022). Farklı coğrafi kökenlere ait kapari meyvelerinden elde edilen ekstrelerin lipopolisakkarit ile uyarılmış inflamatuar hücre modellerinde belirgin anti-inflamatuar aktivite sergilediği ve bu aktivitenin coğrafi kökene bağlı olarak farklılaştığı bildirilmiştir (Alsharif ve Boylan, 2025). Kapari ekstreleri çok sayıda bakteri ve mantar türüne karşı antimikrobiyal etki göstermektedir. Metanolik ve sulu ekstrelerin çeşitli Gram-pozitif ve Gram-negatif bakteri suşlarına karşı inhibitör etkisi bildirilmiş olup bu etkinin ekstredeki fenolik ve flavonoit içeriğiyle ilişkili olduğu bildirilmiştir (AlMousa vd., 2022). Yaprak uçucu yağının; çoğunlukla dimetil trisülfit, dimetil tetrasülfit ve metil izotiyosiyanat gibi kükürt içeren bileşiklerden oluştuğu ve bu bileşenlerin Listeria monocytogenes, Staphylococcus aureus, Escherichia coli, Salmonella ve Pseudomonas gibi gıda kaynaklı patojenlere karşı etkili olduğu, bu özelliğin kaparinin doğal bir gıda koruyucusu olarak potansiyel kullanımına işaret edilmektedir (Mohaddab vd., 2024). Kapari ekstreleri çeşitli kanser hücre hatları üzerinde sitotoksik ve apoptotik etkiler göstermektedir. Kolorektal kanser (HCT-116), prostat kanseri (PC3), mide kanseri (SGC-7901), meme kanseri (MCF-7) ve hepatoselüler karsinom (HepG2) hücre hatlarında yürütülen çalışmalarda, kapari ekstrelerinin doz bağımlı biçimde hücre canlılığını azalttığı ve apoptozu tetiklediği bildirilmiştir (Kdimy vd., 2022; Alsharif ve Boylan, 2025). Prostat kanseri hücrelerinde yürütülen bir çalışmada, kapari metanol ekstresinin Bcl-2 proteinini baskılayıp Bax proteinini artırarak mitokondriyal apoptotik yolağı aktive ettiği, koloni oluşumunu ve hücre göçünü belirgin biçimde azalttığı, bu etkilerinde ekstrede bulunan kersetin ve kaempferolün rol oynadığı in siliko doking analizleriyle desteklenmiştir. Ayrıca kaparinin doksorubisin kaynaklı kardiyotoksisiteye karşı kardiyomiyoblast hücrelerini koruyucu etki gösterdiği de bildirilmiştir (Alsharif ve Boylan, 2025). Yukarıda sayılan başlıca etkilerin yanı sıra kaparinin hepatoprotektif, kardiyoprotektif, antihipertansif, anti-alerjik ve antihistaminik, antiviral, anti-Helikobakter pylori, antiparaziter, antimutajenik, melanogenez uyarıcı ve böcek öldürücü (insektisidal) gibi çok çeşitli farmakolojik etkileri bulunmaktadır (Nabavi vd., 2016; Sun vd., 2023).

Geleneksel Tıpta Kullanımı

Capparis spinosa L., Greko-Arap, Çin, İran ve Ayurveda tıp sistemleri başta olmak üzere dünyanın birçok bölgesinde geleneksel tıbbın önemli bitkilerinden biri olarak kabul edilmektedir (Annaz vd., 2022). İran geleneksel tıbbında kaparinin kök ve tomurcuklarının; felç, uyuşukluk, eklem ağrıları ve siyatalji gibi rahatsızlıkların tedavisinde, yaprak veya kök kabuğunun çiğnenmesinin ise diş ağrısını hafifletmek amacıyla kullanıldığı bildirilmektedir. Meyvelerin ve tuzlanmış köklerin müshil (laksatif) olarak, sirke ve balla hazırlanan kaparinin ise karaciğer tıkanıklığı ve böbrek taşlarının tedavisinde kullanıldığı belirtilmektedir. Fas'ta kapari diyabet kontrolü ve tedavisinde geleneksel olarak tüketilen bir bitkidir. Tunus'ta meyve, tohum ve yapraklarının çeşitli rahatsızlıklarda kullanıldığı bildirilmektedir (Annaz vd., 2022). Türkiye'de bitki bölgelere göre kapari, gebre otu, gevil, kebere, geyil, bubu ve şebellah gibi farklı yerel adlarla anılmaktadır. Çiçek tomurcukları, meyvesi ve kök kabuğunun idrar söktürücü, kabız giderici ve kuvvet verici özelliklere sahip olduğu geleneksel bilgi olarak aktarılmaktadır (Yeğenoğlu ve Uz, 2011).

Gıda İşleme, Tarımsal ve Ekonomik Önemi

Kaparinin ekonomik değerinin temelini açılmamış çiçek tomurcuklarının (kaper) gıda amaçlı kullanımı oluşturmaktadır. Bu şekilde işlenen kaper, salamura ya da sirkeli konserve formunda uluslararası pazarlarda ticareti yapılan bir ürün hâline gelmektedir (Sun vd., 2023; Mohaddab vd., 2024). Türkiye'de kapari, geleneksel olarak doğadan toplanan yabani bitkilerden elde edilmekte olup ihracat ve işlenmiş ürün talebi nedeniyle ekonomik önem taşımaktadır. Kaparinin kurak ve yarı kurak koşullara olan yüksek toleransı; iklim düzensizlikleri etkilerinin giderek belirginleştiği Doğu Akdeniz ülkelerinde alternatif ve sürdürülebilir bir tarım ürünü olarak öne çıkmasını sağlamaktadır (Chedraoui vd., 2017). Derin kök sistemi sayesinde toprak erozyonunun önlenmesinde etkili bir bitki olarak da değerlendirilen kapari, normal tarım bitkilerinin yetişemediği güneye bakan eğimli arazilerde yetiştirilerek hem kırsal alanlarda istihdam yaratılmasına hem de ihracat gelirlerinin artırılmasına katkı sağlayabilecek bir potansiyele sahiptir.

Bazı çalışmalar kapari ekstrelerinin akut toksisite açısından düşük riskli olduğunu, bazı hayvan deneyli çalışmalarında akut toksisite belirtisi gözlenmediği bildirilmiştir (Sun vd., 2023; Annaz vd., 2022). Mevcut toksisite verilerinin sınırlı sayıda çalışmaya dayanması nedeniyle; özellikle uzun süreli kullanım, gebelik-emzirme dönemi ve olası ilaç etkileşimleri açısından daha kapsamlı klinik ve preklinik güvenlik çalışmalarına ihtiyaç duyulduğu belirtilmelidir.

Arıcılık Açısından Önemi ve Arı Merası Potansiyeli

Capparis türleri özellikle Akdeniz ve yarı kurak iklim kuşaklarında arıcılık açısından değerlendirilen bitkiler arasındadır. *C. spinosa*'nın arı merası olarak önemini değerlendirmek için çiçeklenme dönemi, nektar ve polen üretimi, tozlaşma ilişkileri ve balın kimyasal özellikleri birlikte ele alınmalıdır. Kapari çiçeklerinin renk, koku ve gece/alacakaranlıkta açılma özellikleri tozlaştırıcılarla etkileşim açısından dikkat çekmektedir. Eisikowitch vd. (1986), *Capparis* türlerinde nektar ve polen miktarının ekolojik koşullara ve taksona göre değişebildiğini bildirmiştir. Petanidou vd. (1996), *C. spinosa* nektarının hacim, şeker ve amino asit bileşiminin çiçeğin yaşı ve lokasyona göre değiştiğini göstermiştir. Zhang ve Tan (2009), erkek ve hermafrodit çiçeklerde polen üretimi ile nektar özelliklerinin farklılaşabildiğini; Kantsa vd. (2022) ise çiçek rengi ve kokusunun tozlaştırıcı etkileşimleriyle ilişkili olabileceğini bildirmiştir. Bu bulgular, *C. spinosa*'nın tozlaştırıcılar açısından kaynak sağlayabildiğini desteklemektedir. Bal arısı takviyeli doğal tozlaşmada salkım başına ortalama meyve tutum sayısının 4,36, yalnızca bal arıları ile yapılan tozlaşmada 3,77 ve doğal tozlaşmada ise 2,2 olduğu tespit edilmiştir. Çimlenme yüzdeleri, toplam şeker, ortalama meyve ağırlığı, sürgün uzunluğu ve fide uzunluğu, tüm uygulamalar arasında en yüksek bal arısı takviyeli doğal tozlaşma durumunda görülmüştür (Bhatnagar vd., 2023). Tripodi vd. (2025) tarafından *C. spinosa* balının aroma ve duyusal özelliklerinin karakterize edilmesi, türün bal üretimi açısından da araştırılabilir bir kaynak olduğunu göstermektedir. Kapari kuraklığa dayanıklılığı nedeniyle arı merası planlamasında değerlendirilebilecek türlerden biridir. Bununla birlikte, arı merası kurulumu açısından yalnızca nektar/polen varlığı değil; çiçeklenme yoğunluğu, süreklilik, arı ziyaret sıklığı, bal verimi ve yerel iklim koşulları da dikkate alınmalıdır. Kaparinin erozyon kontrolü ve marjinal arazilerin değerlendirilmesi amacıyla kullanılabilmesi, bu tür alanlarda arıcılık amaçlı bitkilendirme ile birlikte ele alınabilecek ek bir avantajdır (Chedraoui vd., 2017; Isagaliev vd., 2022). Türkiye'de farklı floristik araştırmalarda kaparinin bal arılarının yararlanabileceği bitkiler arasında kaydedildiği görülmektedir. Yozgat florası, Artvin, Bitlis ve Düzce'deki çalışmalar ile Türkiye'deki geleneksel arıcılık üzerine yapılan etnobotanik değerlendirmeler; kaparinin nektar ve/veya polen kaynağı olarak kayda geçtiğini göstermektedir (Taştan, 2021; Akyıldırım Beğen vd., 2025; Görhan ve Öztürk, 2021; Kanoğlu vd., 2023; Atsay ve Çakır, 2022).

Ancak bu floristik kayıtlar kaparinin her bölgede başlıca veya sürekli nektar kaynağı olduğunu tek başına kanıtlamaz. Türkiye'nin farklı ekolojik bölgelerinde arı ziyaretleri, nektar/polen verimi ve bal veriminin birlikte ölçüldüğü alan çalışmalarına ihtiyaç vardır.

SONUÇ VE ÖNERİLER

Capparis spinosa L.'nin kurak ve yarı kurak koşullara uyumu, çeşitli fitokimyasal bileşenleri, gıda amaçlı kullanımı ve araştırılan biyolojik aktiviteleri nedeniyle çok yönlü bir bitkidir. Farklı kullanım alanları, kimyasal içeriği ve yararları göz önünde bulundurulduğunda kaparinin hem tarımsal açıdan hem de arıcılık açısından önemli bir potansiyel taşıdığı görülmektedir. Türkiye'de *C. spinosa* ve *C. ovata*'nın doğal yayılış göstermesi, bu türlerin kurak ve yarı kurak alanların değerlendirilmesinde

kullanılma potansiyeline sahip olduğunu göstermektedir. Arıcılık açısından mevcut çalışmalar, *C. spinosa*'nın nektar ve polen kaynağı olabildiğini ve *C. spinosa* balının karakterize edilebildiğini göstermektedir. Ayrıca türün arı merası olarak yaygınlaştırılmasına ilişkin önerilerin yerel fenoloji, nektar/polen verimi, arı ziyaret sıklığı ve bal verimi verileriyle desteklenmesi oldukça önemlidir. Bu nedenle farklı bölgelerde kapari temelli arı merası denemelerinin yapılması ve elde edilen balın melissopalinolojik ve kimyasal özelliklerinin belirlenmesi önem taşımaktadır.

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MISIRIN (ZEA MAYS L.) ARICILIK AÇISINDAN ÖNEMİ VE ARI MERASI OLARAK KULLANILMA POTANSİYELİNİN DEĞERLENDİRİLMESİ

THE IMPORTANCE OF CORN (ZEA MAYS L.) FOR BEEKEEPING AND EVALUATION OF ITS POTENTIAL TO BE USED AS A BEE PASTURE

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ÖZET
Mısır (*Zea mays* L.) dünya genelinde geniş alanlarda yetiştirilen ve üreticiler tarafından yoğun olarak tercih edilen tahıllardan biridir. Rüzgarla tozlaşan (anemofil) bir tür olmasına karşın erkek çiçek salkımlarından (püskül) ürettiği önemli miktardaki polen sayesinde bal arıları (*Apis mellifera* L.) başta olmak üzere birçok arı türü için önemli bir polen kaynağıdır. Bu derlemede; mısırın çiçeklenme biyolojisi, polen üretim kapasitesi, arılar tarafından toplanma davranışı, poleninin besinsel (özellikle protein ve amino asit) değeri, mısır tarımında yaygın kullanılan tohum ilaçlamalarının ve transgenik çeşitlerin arı sağlığına etkileri, mısır üretiminin arı merası çeşitliliği ve koloni beslenme dinamikleri üzerindeki etkileri ile mısırdan elde edilen yüksek fruktozlu mısır şurubunun arı beslemesindeki kullanımı literatür ışığında değerlendirilmiştir. Mısır nicelik olarak zengin ancak nitelik olarak sınırlı bir polen kaynağıdır. Tarımsal uygulamalar nedeniyle bal arısı sağlığı açısından hem fırsat hem de risk barındırmaktadır. Sonuç olarak, mısırın arı merası olarak potansiyeli tek başına değil, çiçeklenme dönemi dışında tamamlayıcı nektar ve polen kaynaklarının sağlanması ve pestisit maruziyetinin azaltılmasıyla birlikte değerlendirildiğinde önemli hale gelmektedir.
Anahtar Kelimeler: ***Z****ea mays*, beekeeping, bee pasture, pollen source, *Apis mellifera*

ABSTRACT
Maize (*Zea mays* L.) is one of the cereals grown over wide areas globally and heavily preferred by producers. Although it is a wind-pollinated (anemophilous) species, thanks to the significant amount of pollen it produces from its male inflorescences (tassels), it serves as an important pollen source for many bee species, primarily honey bees (*Apis mellifera* L.). In this review; maize's flowering biology, pollen production capacity, foraging behavior by bees, nutritional value of its pollen (especially protein and amino acids), the impacts of seed treatments and transgenic varieties widely used in maize cultivation on bee health, the effects of maize production on bee forage diversity and colony nutrition dynamics, and the use of high-fructose corn syrup derived from maize in bee feeding have been evaluated in the light of the literature. Maize is a rich pollen source quantitatively, but limited qualitatively. Due to agricultural practices, it harbors both opportunities and risks in terms of honey bee health. In conclusion, the potential of maize as a bee forage becomes significant when evaluated not on its own, but together with the provision of complementary nectar and pollen sources outside the flowering period and the reduction of pesticide exposure.
Keywords: Zea mays, apiculture, bee pasture, pollen source, Apis mellifera, neonicotinoid

GİRİŞ
Mısır (*Zea mays* L.) buğdaygiller (Poaceae) familyasına ait, tek yıllık, C4 fotosentez metabolizmasına sahip bir bitki olup dünya genelinde buğday ve pirinçle birlikte en fazla üretilen üç tahıldan biridir. İnsan ve hayvan beslenmesinde, nişasta, biyoyakıt ve endüstriyel şeker (yüksek fruktozlu mısır şurubu) üretiminde kullanılması nedeniyle ekim alanı son yıllarda hızla genişlemiştir. Bu dönüşüm, tarım alanlarında yaşayan veya bu alanlara komşu konumlanan bal arısı (*Apis mellifera* L.) kolonileri açısından hem doğrudan hem de dolaylı sonuçlar doğurmaktadır.

Arıcılık literatüründe bitkiler geleneksel olarak nektar bitkileri ve polen bitkileri olmak üzere iki temel kategoriye ayrılır. Mısır, rüzgarla tozlaşan (anemofil) bir tür olduğu için böcek çekici nektar üretmez; ancak erkek çiçek salkımı olan püskülden (tassel) kısa bir dönemde inanılmaz miktarda polen üretmektedir. Bu özelliği, mısırı klasik anlamda bir "bal bitkisi" olmaktan çıkarırken, bal arıları başta olmak üzere birçok arı türü için önemli bir polen kaynağına dönüştürmektedir (Höcherl ve ark., 2012; Chantarudee ve ark., 2012). Nitekim tarımsal üretimde polen tuzakları kullanılarak yapılan çalışmalar,

mısırın çiçeklenme döneminde arı kovanlarına giren toplam polenin önemli bir kısmının mısır kaynaklı olduğunu ortaya koymaktadır. Bununla birlikte, mısırın arıcılık açısından değerlendirilmesi yalnızca polen bolluğu üzerinden yapılamaz. Mısır poleninin protein ve esansiyel amino asit içeriği, birçok yabani ve kültür bitkisininkine kıyasla düşüktür (Roulston ve ark., 2000; Pamminger ve ark., 2019). Ayrıca modern mısır tarımında yaygın olarak kullanılan neonikotinoid grubu sistemik insektisitlerle kaplı tohumlar, ekim sırasında ortaya çıkan toz bulutu yoluyla arı ölümlerine ve kronik zehirlenmelere yol açabilmektedir (Krupke ve ark., 2012; Tsvetkov ve ark., 2017). Bir diğer madde ise, mısır ve soya gibi tek yıllık endüstriyel bitkilerin hâkim olduğu üretim alanlarında arı kolonilerinin mevsim içinde yaşadığı ziyafet-kıtlık dinamiğidir; kısa süreli bol kaynak dönemlerini uzun kıtlık dönemleri izlemektedir (Dolezal ve ark., 2019).

Bu derlemenin amacı; mısırın (*Zea mays* L.) arıcılık açısından önemini ve arı merası olarak kullanılma potansiyelini, botanik ve çiçeklenme biyolojisini, polen kalitesini, tarımsal uygulamaların arı sağlığına etkilerini, üretim ölçeğinde arı merası dinamikleri ve mısır kaynaklı ürünlerin arı beslemesindeki yerini incelemektedir.

MATERYAL VE YÖNTEM

Bu çalışma; mısır (*Zea mays* L.) yetiştiriciliği, kalitesi, fiziksel, kimyasal özelikleri, yetiştiricilik uygulamaları, döllenme biyolojisi ve mısır-arı ilişkilerinin literatüre dayalı incelenmesi ve değerlendirilmesi ile oluşturulmuştur. Mısırın genel özelikleri ve mısır-arı ilişkileri konusundaki internet kaynaklarından ve veri tabanlarından yararlanılmıştır. Bu çalışma ilgili kaynakların taranması, kaynakların çeşitli açılardan değerlendirilmesi, yorumlanması ve sentezlenmesi ile mısırın arıcılık için önemi ve arı merası olarak değerlendirilme potansiyelini ortaya koymaya odaklanmıştır.

BULGULAR ve TARTIŞMA

Mısırın Botanik Özellikleri ve Çiçeklenme Biyolojisi

Mısır, tek gövdeli, 1,5-3 metre boylanabilen, monoik (tek evcikli) bir bitkidir. Erkek çiçek topluluğu bitkinin tepe noktasında yer alan püskül (tassel) şeklinde, dişi çiçek topluluğu ise gövde üzerindeki yaprak koltuklarında oluşan koçan (mazorca) şeklindedir. Koçanın ucundan dışarı sarkan uzun, ipliksi stigma yapıları (silk/tepecik iplikçikleri) polen alıcı yüzeyi oluşturur. Bu yapılar silk çıkışından sonra günler boyunca polen almaya elverişli kalabilmekte, tepecik yüzeyindeki trikom (tüycük) yoğunluğu ise çeşide göre değişerek polen tutma etkinliğini belirlemektedir (Anderson ve ark., 2004). Bitkinin erkek ve dişi çiçeklerinin genellikle farklı zamanlarda olgunlaşması (protandri), kendine döllenme oranını düşürerek çapraz tozlaşmayı teşvik etmektedir; buna karşın silklerin polen alıcılığı çoğunlukla püskülden polen saçılımı başlamadan önce devreye girmektedir (Anderson ve ark., 2004). Mısır, tipik bir anemofil bitkidir. Anemofil (rüzgarla tozlaşan) türlerde, hedefe ulaşan polen oranının düşük olmasını telafi etmek ve tozlaşma başarısını şansa bırakmamak amacıyla orantısız derecede yüksek miktarda polen üretilmesi stratejisidir (Bochynek ve Burd, 2024). Mısır bu stratejinin tarımsal açıdan en belirgin örneklerinden biridir. Bireysel bir mısır bitkisinin püskülü döllenme için gerekli minimum miktarın kayda değer ölçüde, ortalama olarak milyonlarca polen tanesi üretebilmektedir. Bu aşırı üretim genel olarak mısırda pollen kaynağının kısıtlayıcı bir etken olarak görülmemesinin başlıca nedenidir (Westgate ve ark., 2003). Bir tek bitkinin püskülünden polen saçılımı genellikle 5-6 gün sürerken, tarla düzeyinde çeşit ve çevre koşullarına bağlı olarak toplam çiçeklenme süresi 2-14 gün arasında değişebilmektedir (Westgate ve ark., 2003; Wang ve ark., 2022). Bu yoğun üretim rüzgarla taşınma sırasında meydana gelen kayıpları telafi etmeye yöneliktir. Ayrıca üretim alanı açısından değerlendirildiğinde, çiçeklenme döneminde havada yoğun bir polen bulutu oluşmasına neden olur.

Bu polen bolluğunun zamanlaması arıcılık açısından kritik öneme sahiptir. Mısır tarlalarının çiçeklenme dönemi (genellikle yaz ortası, temmuz-ağustos ayları), birçok bölgede diğer kültür bitkilerinin çiçeklenmesinin sona erdiği ve doğal florada da nektar/polen akışının azaldığı bir döneme denk gelmektedir. Bu nedenle mısır tarımsal üretimde mevsimsel kıtlık dönemi olarak adlandırılan kritik bir zaman aralığında devreye giren, geçici fakat önemli bir polen kaynağı işlevi görebilmektedir (Höcherl ve ark., 2012; Deveci ve ark., 2015).

Mısırın Bal Arıları İçin Polen Kaynağı Olarak Değerlendirilmesi

Bal arıları, çiçeklenme döneminde mısır tarlalarını yoğun biçimde ziyaret ederek polen toplarlar. Brezilya'da yürütülen bir tarla denemesinde; bal arılarının mısır püskülündeki erkek çiçeklerden yoğun

biçimde polen topladığı ve mısır poleninin özellikle diğer polen kaynaklarının kıt olduğu dönemlerde arılar için önemli bir besin kaynağı olarak değerlendirildiği gösterilmiştir (Malerbo-Souza, 2011). ABD'de yürütülen çalışmasında; bal arılarının mısır poleni toplama etkinliğinin sabah saatlerinde (yaklaşık 09:00-10:00) zirveye ulaştığı belirlenmiş, tarımsal ilaçlama zamanlamasının arı maruziyeti açısından önemine işaret ettiği vurgulanmıştır (Mason ve Tracewski, 1982). Almanya'da yürütülen bir çalışmada ise mısırın yoğun biçimde kullanılan bir polen kaynağı olduğu, buna karşın arıların mısır poleni için kat ettiği ortalama mesafenin diğer polen kaynaklarına kıyasla daha kısa kaldığı ve mısır ekim alanı genişledikçe mısır poleni toplayan arı oranının orantılı biçimde artmadığı bildirilmiştir (Danner ve ark., 2014). Tayland'da *Apis mellifera* kolonilerinden toplanan polenler ile tarladan toplanan polenlerin karşılaştırılması sonucu; arı tarafından işlenmiş polenin biyotin, invert şeker, A vitamini, beta-karoten gibi besin bileşenleri açısından zengin olduğu ve serbest radikal süpürücü aktivitesinin tarladaki polenden 28 kat daha fazla olduğu bulunmuştur (Chantarudee ve ark., 2012). Tayland'daki ticari arı poleni üretiminde de mısır (*Zea mays*), kolza, çay ağacı, lotus gibi bitkilerle birlikte başlıca on bir polen kaynağından biri olarak sayılmakta; yılda 700 tonu aşan ticari arı poleni üretiminin önemli bir bölümü bu kaynaklardan elde edilmektedir. Bu durum, mısırın yalnızca koloni içi beslenme değil, ticari arı poleni üretimi için de kullanıldığını ortaya koymaktadır. Polenin besin değeri değerlendirilirken en sık kullanılan gösterge ham protein içeriğidir. Polen; bal arısı kolonisinde larva gelişimi, hipofarengeal bez fonksiyonu ve genel bağışıklık için ana protein kaynağıdır. Roulston, Cane ve Buchmann (2000), 93 bitki familyasından 377 türü incelendiği çalışmada; polen protein içeriğinin bitki filogenisi ile güçlü biçimde ilişkili olduğu ve zoofil türlerin anemofil türlerden istatistiksel olarak daha zengin protein içermediği bildirilmektedir. Pamminger ve ark. (2019) tarafından yürütülen derlemede, mısır ve ayçiçeğinin, arı tarafından ziyaret edilen tarımsal bitkiler arasında ham protein içeriği en düşük polen kaynakları arasında yer aldığı belirtilmiştir. Höcherl ve ark. (2012) tarafından yapılan çalışmada; mısır poleninde histidin amino asidinin belirgin biçimde düşük olduğunu, buna karşın diğer tüm esansiyel amino asitlerin miktarının polifloral karışıma göre daha yüksek çıktığını, mısır poleninin genel kabul edilenin aksine tamamen değersiz olmadığını, ancak dengeli bir amino asit profili sunmadığı için tek başına yeterli bir protein kaynağı oluşturmadığını göstermektedir. Fransa'da arı kolonilerinin mevsim boyunca topladığı polen karışımlarının koloni sağlığı (işçi arı hayatta kalma oranı ve hipofarengeal bez gelişimi) üzerindeki etkisini çalışmada; polen karışımlarının çoğunun arı sağlık göstergeleri üzerinde benzer olumlu etkiye sahip olduğu, buna karşın temmuz sonunda toplanan ve yoğun biçimde mısır poleni barındıran karışımın arının hayatta kalma oranı ve arı fizyolojisi üzerinde belirgin olumsuz sonuç doğurduğu; bu dönemin mısırın kitlesel çiçeklenme dönemine denk geldiği bildirilmiştir (Di Pasquale ve ark., 2016).Yukarıdaki bulgular birlikte değerlendirildiğinde, mısırın arıcılık açısından nicelik olarak zengin, nitelik olarak sınırlı bir polen kaynağı olduğu söylenebilir. Mısır tarlalarına yakın konulan kolonilerde toplam polen miktarı artar, ancak beslenme kalitesi diğer kaliteli polen kaynaklarının (baklagiller, Asteraceae, Brassicaceae vb.) mevcudiyetine bağlı kalmaya devam eder.

Mısır Tarımında Kullanılan Uygulamaların Arı Sağlığına Etkileri

Mısırın arı merası potansiyeli değerlendirilirken yalnızca bitkinin doğal polen değeri değil, aynı zamanda modern mısır tarımında standart hale gelmiş agronomik uygulamaların arı sağlığı üzerindeki etkileri de göz önünde bulundurulmalıdır. Neonikotinoid grubu sistemik insektisitlerin bal arıları ve diğer polinatörler üzerindeki etkilerine ilişkin çalışmada; insektisitlerin tohum kaplaması yoluyla toksik maruziyet yollarını, laboratuvar koşullarında gözlenen letal ve subletal etkileri ve polinatör ürünlerindeki kalıntı düzeylerini belirtilmiştir (Godfray ve ark., 2014). Amerika başta olmak üzere birçok ülkede ekilen mısır tohumlarının büyük bölümü tohumu toprak kökenli zararlılardan korumak amacıyla neonikotinoid grubu sistemik insektisitler ile kaplanmaktadır (Lin ve ark., 2021). Tohum kaplamasının pnömatik ekim makinelerinde sürtünme yoluyla aşınması ile insektisit yüklü ince bir tozun havaya karışmasına yol açar; bu toz bulutu ekim alanının çevresine ve civardaki çiçekli bitkilere taşınarak arı ölümüne neden olmaktadır (Lin ve ark., 2021; Samson-Robert ve ark., 2017). Krupke ve ark. (2012) tarafından yapılan çalışmada; mısır ve soya ekim alanlarına komşu arılarda ve kovan çevresindeki bitkilerde neonikotinoid kalıntılarının tespit edildiği bildirilmiştir. Krupke ve ark. (2017), Indiana eyaletinde ekim sırasında oluşan neonikotinoid tozunun tarla kenarından 100 metre uzaklıktaki çiçeklere kadar gidebildiğini, arı kolonilerinin büyük çoğunluğunun mısır ekimi sırasında öldürücü dozlara maruz kalmasına rağmen bu tohum ilaçlamalarının tutarlı bir bitki verim artışı sağlamadığını bildirmiştir. Long ve Krupke (2016) tarafından yapılan çalışmada; arıların neonikotinoid maruziyetinin

yalnızca mısır ekim dönemiyle sınırlı olmadığı, yabani bitkilerin de büyüme dönemi boyunca neonikotinoid kalıntısı taşıdığı ve kirlenmenin toprak ve yeraltı suyu yoluyla civar bitkilere taşındığını bildirilmiştir. Tsvetkov ve ark. (2017), mısır tarlalarına yakın kolonilerin sezonun büyük bölümünde (3-4 ay) neonikotinoidlere kronik olarak maruz kaldığını; bu maruziyetin işçi arı ölüm oranını artırdığını, sosyal bağışıklığı zayıflattığını ve zaman içinde anasız kalma oranını yükselttiğini bildirmiştir. Kanada'nın Québec eyaletinde yürütülen bir çalışmada; mısır tarımının yoğun olduğu bölgelerdeki kolonilerde günlük arı ölüm sayısının, mısır ekilmeyen bölgelerdeki kolonilere kıyasla 3,5 kat daha yüksek olduğunu, ölen arılarda çok sayıda farklı tarımsal pestisit kalıntısının aynı anda tespit edildiği bildirilmiştir (Samson-Robert ve ark., 2017). Bu bulgular birlikte değerlendirildiğinde, mısır tarımının modern, tohum-kaplama temelli koruma stratejisinin, bitkinin sunduğu polen kaynağı potansiyelini önemli ölçüde gölgeleyen bir risk faktörü oluşturduğu ortaya çıkmaktadır.

Böcek zararlılarına karşı dayanıklılık sağlamak amacıyla Bacillus thuringiensis bakterisinden alınan Cry protein genlerini taşıyan mısır çeşitleri, dünya genelinde yaygın olarak ekilmektedir.

Duan ve ark. (2008) tarafından yapılan çalışmada; Bt mısır ve pamuk çeşitlerinde kullanılan Cry proteinlerinin laboratuvar koşullarında larva ve erişkin bal arılarına zarar vermediği bildirilmiştir. Hendriksma ve ark. (2013), Bt mısır poleniyle beslenen arılarda hayatta kalma oranı, vücut ağırlığı ve polen sindirim oranı bakımından konvansiyonel mısır çeşitleriyle beslenenlere kıyasla anlamlı bir fark bulmamıştır. Aynı çalışmada, tam gelişmiş işçi arı larvalarının sindirim sistemlerinde 1720-2310 adet mısır polen tanesi (larva başına yaklaşık 1,52-2,04 mg polen) tespit edilmiştir. Bu polenlerin yaklaşık %74,5'inin tamamen, %23,3'ünün kısmen sindirildiği, yalnızca %2,2'sinin sindirilmeden kaldığı belirlenmiştir.

Bu bulgular bir arada değerlendirildiğinde, mevcut bilimsel kanıtların, ticarileştirilmiş Bt mısır çeşitlerinde kullanılan Cry proteinlerinin bal arıları için doğrudan toksik bir risk oluşturmadığı söylenebilir.

Mısır Kaynaklı Ürünlerin Arı Beslemesinde Kullanımı: Yüksek Fruktozlu Mısır Şurubu

Mısırın arıcılıkla ilişkisi yalnızca tarla düzeyinde polen kaynağı olmasıyla sınırlı değildir. Mısır nişastasından endüstriyel olarak üretilen yüksek fruktozlu mısır şurubu özellikle Kuzey Amerika'da ticari arıcılıkta yaygın bir tamamlayıcı besleme kaynağı olarak kullanılmaktadır. Bal hasadı sonrası kolonilerin karbonhidrat ihtiyacını karşılamak, nektar akışının kesildiği dönemlerde besleme yapmak ya da yavru üretimini teşvik etmek amacıyla tercih edilen şurup, maliyet avantajı nedeniyle sakaroz şurubuna alternatif olarak yaygın biçimde kullanılmaktadır.

Ancak şurubun ısıya ve depolama koşullarına duyarlı bir bileşik olan hidroksimetilfurfural açısından risk taşıdığı bilinmektedir. Le Blanc ve ark. (2009), sıcaklık arttıkça ve depolama süresi uzadıkça HMF düzeyinin belirgin biçimde yükseldiğini, yüksek düzeylerdeki HMF'nin bal arılarında bağırsak ülserasyonu ve dizanteri benzeri belirtilere yol açarak toksik etki gösterebildiğini bildirmiştir.

Arıcıların YFMŞ kullanırken ürünü aşırı ısıtmaktan kaçınması, uzun süreli ve sıcak ortamlarda depolamaması, mümkün olduğunda düşük HMF içerikli şuruplar veya sakaroz temelli alternatifleri tercih etmesi dikkat edilmesi gereken hususlardandır.

SONUÇ

Bu derleme, mısırın (*Zea mays* L.) arıcılık açısından önemini ve arı merası olarak kullanılma potansiyelini ele almıştır. Elde edilen bulgular, mısırın rüzgarla tozlaşan bir bitki olmasına karşın, üretkenliği son derece yüksek püskül yapısı sayesinde bal arıları için önemli bir dönemsel polen kaynağıdır. Ancak bu polenin protein ve amino asit içeriği bakımından sınırlı besinsel değere sahiptir. Modern mısır tarımının ayrılmaz bir parçası hâline gelen neonikotinoid tohum ilaçlamaları, bitkinin sunduğu bu sınırlı faydayı gölgeleyebilecek düzeyde ciddi bir arı sağlığı riski oluşturmaktadır. Transgenik (Bt) çeşitlerde kullanılan Cry proteinlerinin arılara doğrudan bir tehdit oluşturmadığı tespit edilmiştir. Mısır üretim alanlarının arı merası çeşitliliğini azaltarak kolonilerde mevsimsel ziyafet-kıtlık dinamiğine yol açtığı, ancak bu olumsuz etkinin doğal/yarı doğal bitki örtüsü ile desteklenen alanlarda büyük ölçüde telafi edilebileceği görülmektedir. Dolayısıyla mısırın arı merası olarak gerçek potansiyeli, bitkinin kendi başına taşıdığı özelliklerden çok, içinde yer aldığı tarımsal üretimin bütünsel yapısına, doğal ya da yarı doğal bitkilerin varlığına ve uygulanan bitki koruma ürünlerine bağlıdır.

Sonuç olarak, mısır arı merası kurulumunda göz ardı edilmemesi gereken, dönemsel ve tamamlayıcı bir polen kaynağı olarak değerlendirilmeli, sürdürülebilir bir katkı sağlaması için tarımsal alanların floral

çeşitlilik açısından zenginleştirilmesi, tohum ilaçlaması kaynaklı akut ve kronik pestisit maruziyetinin azaltılması ve arı beslemesinde kullanılan mısır kaynaklı yardımcı ürünlerin güvenli koşullarda saklanması gibi tamamlayıcı önlemlerle bir arada ele alınmalıdır. Türkiye özelinde bu potansiyelin doğrulanabilmesi için arı bitki ilişkisini inceleyen çalışmalara, tarımsal ürün kovan karşılaştırmalarına, arıları davranışlarını inceleyen vb. çalışmalara ihtiyaç duyulmaktadır.

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SİVAS İLİ SULU TARIM, ENDÜSTRİYEL VE YEM BİTKİLERİ DESENİ

CROPPING PATTERN OF IRRIGATED AGRICULTURE, INDUSTRIAL AND FORAGE CROPS IN SIVAS (TÜRKİYE)

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Özet

Bu çalışmada, sulu tarım, endüstriyel üretim ve yem bitkileri deseni kapsamında söz konusu ürünlerin 2020-2024 dönemindeki ekiliş alanı, üretim miktarı ve verim değişimlerinin değerlendirilmesi amaçlanmıştır. Bu kapsamda; Sivas ilinde şeker pancarı, patates, ayçiçeği, yonca, silajlık mısır ve kuru fasulye; üretim miktarı, verim düzeyi ve ürün desenine sağladıkları katkı bakımından öne çıkan bitkisel ürünler arasında yer almaktadır. Şeker pancarında ekiliş alanı 2020 yılında 170.727 dekar iken 2024 yılında 181.976 dekara, üretim miktarı ise 975.782 tondan 1.035.924 tona yükselmiş ve ürün dönem boyunca genel olarak istikrarlı bir yapı göstermiştir. Patates üretiminde daha belirgin bir gelişme gerçekleşmiş ve 2020-2024 yıllarında ekiliş alanı 65.873 dekardan 140.108 dekara, üretim miktarı 192.630 tondan 560.398 tona çıkmış ve Sivas'ın Türkiye patates üretimindeki payı %3,70'ten %8,12'ye ulaşmıştır. Ayçiçeğinde 2020 yılında 2.394 dekar olan ekiliş alanı 2022 yılında 83.337 dekara kadar yükselmiş, üretim miktarı 2023 yılında 22.452 tonla dönem içerisindeki en yüksek seviyeye ulaşmış, 2024 yılında ise ekiliş alanı ve üretimde kısmi bir gerileme görülmüştür. Yem bitkileri içerisinde yonca ekiliş alanı ve üretim miktarında azalma meydana gelmesine rağmen verim 2021 sonrasında yeniden artarak 2024 yılında 786 kg/da düzeyine ulaşmıştır. Silajlık mısırda 2020 yılında 20.484 dekar olan ekiliş alanı 2024 yılında 24.893 dekara, üretim miktarı 94.473 tondan 122.973 tona yükselmiş; aynı yıl 4.940 kg/da ile dönemin en yüksek verimi elde edilmiştir. Silajlık mısırın özellikle sulama imkânlarının bulunduğu arazilerde yetiştirildiği, yoncada ise sulama ve gübreleme yönetiminin verimliliği desteklediği görülmektedir. Kuru fasulye üretimi yıllar arasında dalgalı bir yapı göstermiş; ekiliş alanı 2022 yılında 6.770 dekar ve üretim 946 ton ile en yüksek seviyesine ulaşmış, 2024 yılında ise sırasıyla 4.910 dekar ve 699 ton olarak gerçekleşmiştir. Sonuç olarak, incelenen ürünler Sivas'ta üretim deseninin çeşitlenmesi ve birim alandan farklı düzeylerde üretim sağlanması bakımından önemli bir potansiyel ortaya koymaktadır. Ürünler arasında ekiliş alanı, üretim ve verim bakımından farklı eğilimlerin bulunması, üretim planlamasının ürün bazında ve bölgesel koşullar dikkate alınarak yapılmasının önemini göstermektedir.

Anahtar kelimeler: Şeker pancarı, patates, ayçiçeği, yem bitkileri, silajlık mısır, ürün

Abstract

This study aimed to evaluate the changes in cultivated area, production quantity, and yield of the relevant crops during the 2020-2024 period within the scope of irrigated agriculture, industrial production, and forage crop patterns. In this context, sugar beet, potato, sunflower, alfalfa, silage maize, and dry bean are among the prominent crops in Sivas Province in terms of production quantity, yield level, and their contribution to the cropping pattern. In sugar beet, the cultivated area increased from 170,727 decares

in 2020 to 181,976 decares in 2024, while production increased from 975,782 tons to 1,035,924 tons, and the crop generally showed a stable structure throughout the period. A more pronounced development occurred in potato production, and between 2020 and 2024 the cultivated area increased from 65,873 decares to 140,108 decares, while production increased from 192,630 tons to 560,398 tons, and the share of Sivas in Türkiye's potato production reached 8.12% from 3.70%. In sunflower, the cultivated area, which was 2,394 decares in 2020, increased to 83,337 decares in 2022, while production reached the highest level of the period at 22,452 tons in 2023, and a partial decline in cultivated area and production was observed in 2024. Among forage crops, although a decrease occurred in alfalfa cultivation area and production quantity, yield increased again after 2021 and reached 786 kg/da in 2024. In silage maize, the cultivated area increased from 20,484 decares in 2020 to 24,893 decares in 2024, while production increased from 94,473 tons to 122,973 tons; in the same year, the highest yield of the period was obtained at 4,940 kg/da. It is observed that silage maize is grown especially in areas where irrigation opportunities are available, while irrigation and fertilization management support productivity in alfalfa. Dry bean production showed a fluctuating pattern among years; the cultivated area reached its highest level at 6,770 decares and production at 946 tons in 2022, while in 2024 these values were 4,910 decares and 699 tons, respectively. In conclusion, the crops examined reveal important potential in terms of diversification of the cropping pattern in Sivas and achieving different levels of production per unit area. The presence of different trends among crops in terms of cultivated area, production, and yield demonstrates the importance of carrying out production planning on a crop-specific basis and by taking regional conditions into consideration.
Keywords: Sugar beet, potato, sunflower, forage crops, silage maize, cropping pattern

GİRİŞ

Tarımsal üretim sistemlerinin sürdürülebilirliği, üretim kaynaklarının etkin kullanılması ve farklı çevresel ve ekonomik koşullara uyum sağlayabilecek ürün desenlerinin oluşturulmasıyla yakından ilişkilidir. Tek ürüne dayalı üretim sistemleri çevresel ve ekonomik değişkenlik karşısında daha kırılgan bir yapı gösterebilirken, ürün deseninin çeşitlendirilmesi üretim sistemlerinin dayanıklılığının artırılmasına katkı sağlayabilmektedir. Farklı ürünlerin üretim sistemine dahil edilmesi aynı zamanda toprak özellikleri, besin maddesi kullanımı ve tarımsal ekosistem hizmetleri açısından da çeşitli avantajlar sağlayabilmektedir (Lin, 2011; Tamburini vd., 2020).

Ürün deseninin belirlenmesinde su kaynaklarının varlığı ve sulama olanakları temel faktörlerden biridir. Özellikle bitkinin gelişme dönemindeki su gereksiniminin doğal yağışlarla karşılanamadığı koşullarda sulama, üretim miktarı ve birim alan veriminin sürdürülebilmesi açısından önem kazanmaktadır. Bununla birlikte tarımsal su verimliliği yalnızca uygulanan sulama miktarına bağlı olmayıp ürün seçimi, toprak ve bitki besleme yönetimi ile diğer yetiştirme uygulamalarının birlikte değerlendirilmesini gerektirmektedir (Molden vd., 2010). Bu nedenle sulu tarım koşullarında ürün planlaması yapılırken yalnızca yüksek üretim potansiyeline değil, suyun etkin kullanımı ve ürünlerin bölgesel koşullara uyumuna da dikkat edilmesi gerekmektedir.

Tarımsal üretim deseninin çeşitlenmesinde gıda üretiminin yanı sıra sanayiye hammadde sağlayan ürünler de önemli bir yere sahiptir. Şeker pancarı dünya şeker üretiminin önemli kaynaklarından biri olup gıda ve sanayi sektörleriyle doğrudan ilişkili bir endüstri bitkisidir (Tayyab vd., 2023). Patates ise geniş adaptasyon yeteneği, yüksek üretim potansiyeli ve hem doğrudan tüketim hem de işlenmiş gıda sektöründeki kullanımı nedeniyle küresel gıda sisteminin önemli ürünleri arasında yer almaktadır (Devaux vd., 2021). Yağlı tohumlar içerisinde ayçiçeği de bitkisel yağ üretimi ve elde edilen yan ürünlerin yem sektöründeki kullanımı bakımından küresel ölçekte önemli bir tarımsal üründür (Pilorgé, 2020). Bu ürünlerin farklı kullanım alanlarına sahip olması, tarımsal üretim ile gıda ve sanayi sektörleri arasındaki bağlantıyı güçlendirmektedir. Üretim deseninin bir diğer önemli bileşenini yem bitkileri oluşturmaktadır. Bitkisel ve hayvansal üretimin birlikte yürütüldüğü bölgelerde kaliteli kaba yem üretiminin artırılması, hayvancılığın sürdürülebilirliği açısından önem taşımaktadır. Yonca ve silajlık mısır, yüksek yem değerleri ve farklı kullanım özellikleri nedeniyle yaygın olarak yetiştirilen başlıca yem bitkileri arasında yer almaktadır. Türkiye'de de yonca ve silajlık mısır, yem bitkileri üretiminde öne çıkan ürünler arasında bulunmakta ve kaliteli kaba yem ihtiyacının karşılanmasına katkı sağlamaktadır (Tan ve Yolcu, 2021). Bitkisel ve hayvansal üretimin bütünleşik biçimde ele alınması, tarımsal kaynakların daha etkin değerlendirilmesine ve üretim sisteminin farklı bileşenleri arasında tamamlayıcılık oluşturulmasına olanak sağlamaktadır (Lemaire vd., 2014; Martin vd., 2016). Baklagiller

de insan beslenmesine sağladıkları katkının yanında tarımsal üretim sistemleri açısından önem taşımaktadır. Kuru fasulye, yüksek protein, lif ve mineral içeriği nedeniyle dünya genelinde önemli bir besin kaynağı olarak değerlendirilirken, baklagil özelliği ve kısa yetişme dönemi ürün rotasyonlarının çeşitlendirilmesine katkı sağlayabilmektedir (Uebersax vd., 2023). Türkiye'de kuru fasulye üretimi; tüketim, üretim ve pazarlama yapısı bakımından yemeklik tane baklagiller içerisinde önemli bir konuma sahiptir (Küzeci vd., 2019).

Sivas'ta karasal iklim koşulları, geniş tarım alanları, bitkisel üretim ile hayvancılığın birlikte yürütülmesi ve farklı ürün gruplarının yetiştirilebilmesi ilin tarımsal ürün desenini şekillendirmektedir. Sivas koşullarında yapılan çalışmalar, şeker pancarı ve ayçiçeği gibi ürünlerde su kullanımının üretim sistemi açısından değerlendirilmesi gerektiğini ortaya koyarken, farklı yonca çeşitlerinin il ekolojik koşullarındaki verim ve kalite özellikleri de araştırılmıştır (Polat Bulut ve Topal Canbaz, 2022; Karaköy ve Saraç, 2018).

Bu çalışma kapsamında ele alınan 2020-2024 verilerinde de şeker pancarı, patates, ayçiçeği, yonca, silajlık mısır ve kuru fasulyenin ekiliş alanı, üretim miktarı ve verim bakımından birbirinden farklı gelişim eğilimleri gösterdiği görülmektedir. Bu çalışmada söz konusu ürünlerin 2020-2024 dönemindeki değişimlerinin değerlendirilmesi ve Sivas ilindeki üretim deseninin ürün bazında ortaya konulması amaçlanmıştır.

ENDÜSTRİ BİTKİLERİ

Sivas'ta tarıma dayalı sanayinin varlığı ve entegre üretim yapısı, endüstri bitkilerinin il geneline yayılan üretim deseni içerisindeki stratejik önemini her geçen gün artırmaktadır. Bölgenin iklim koşulları ve toprak yapısı doğrultusunda şekillenen bu grup içerisinde, özellikle şeker pancarı, patates ve ayçiçeği öne çıkan ürünler olarak dikkat çekmektedir. Bu ürünler, ekim nöbeti sistemindeki rolleri, su ve yetiştiricilik ihtiyaçları bakımından farklı üretim eğilimleri sergilemekle birlikte; gerek imalat sanayisine girdi sağlayan hammadde nitelikleriyle gerekse kırsal kalkınmaya sundukları yüksek katma değerle hem bölgesel ekonomi hem de tarımsal sürdürülebilirlik için oldukça önemli bir yere sahiptir.

Şeker Pancarı (*Beta vulgaris* L.) Üretimi

Şeker pancarı, dünya şeker üretiminde şeker kamışıyla birlikte temel hammadde kaynaklarından biri olup özellikle ılıman iklim kuşağında önemli bir endüstri bitkisidir. Dünya şeker gereksiniminin yaklaşık dörtte birinin şeker pancarından karşılanması, ürünün gıda sanayisi açısından önemini ortaya koymaktadır (Tayyab vd., 2023). Türkiye'de de şeker pancarı üretimi tarıma dayalı sanayiyle doğrudan ilişkili olup şeker fabrikaları, üretim politikaları ve kırsal ekonomi bakımından önemli bir yapıya sahiptir (Demirdöğen, 2022). Sivas koşullarında şeker pancarının su ayak izinin araştırılmış olması da bu ürünün su kullanımı ve bölgesel üretim yapısı açısından önem taşıdığını göstermektedir (Polat Bulut ve Topal Canbaz, 2022). Bu özellikler, şeker pancarının Sivas'taki üretim seyrinin ekiliş alanı, üretim miktarı ve verim göstergeleri bakımından birlikte değerlendirilmesini önemli hâle getirmektedir.

Bu kapsamda 2020-2024 dönemi incelendiğinde, şeker pancarında ekiliş alanı ve üretim miktarı 2021 yılında belirgin biçimde gerilemiş, izleyen yıllarda yeniden artış göstermiştir. Üretim 2023 yılında bir milyon tonun üzerine çıkmış ve 2024 yılında 1.035.924 tona ulaşmıştır. Sivas'ın Türkiye toplam şeker pancarı ekiliş alanındaki payının dönem boyunca yaklaşık %5 düzeyinde seyretmesi de ürünün il tarımı içerisindeki sürekliliğine işaret etmektedir (Çizelge 1).

2021 yılında görülen düşük üretim ve verimde kuraklık ve olumsuz iklim koşulları etkili olmuş; yağışların mevsim normallerinin altında kalması bitki gelişimini olumsuz etkilemiştir. Sonraki yıllarda üretim yeniden yükselmiş ve Sivas'ta şeker pancarı verimi 2023 yılında 6.149 kg/da ile dönem içerisindeki en yüksek seviyesine ulaşmıştır. Bununla birlikte çizelgedeki değerler karşılaştırıldığında Sivas'ta şeker pancarı veriminin 2020-2024 yıllarının tamamında Türkiye ortalamasının altında kaldığı görülmektedir.

Çizelge 1. Sivas ili şeker pancarı üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	170.727	5,05	975.782	4,24	6.810	5.730
2021	150.174	4,92	798.232	4,49	5.818	5.336
2022	151.393	5,09	841.741	4,37	6.472	5.599

2023	167.305	4,60	1.026.004	4,06	6.936	6.149
2024	181.976	5,53	1.035.924	4,62	6.811	5.700

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Patates (*Solanum tuberosum* L.) Üretimi

Patates, yüksek verim potansiyeli, besin değeri ve farklı iklim bölgelerinde yetiştirilebilmesi nedeniyle dünya gıda sisteminin temel ürünlerinden biridir. Gıda güvenliğine katkısının yanı sıra taze tüketim, işlenmiş gıda ve nişasta gibi farklı kullanım alanlarına sahip olması ürünün ekonomik önemini artırmaktadır (Devaux vd., 2021). Türkiye'de de patates önemli bir bitkisel ürün olup, dış ticaret ve tarımsal destek politikaları açısından ayrı bir üretim yapısına sahiptir (Kadakoğlu ve Karlı, 2021). Bu genel önem içerisinde Sivas'ta son yıllarda görülen üretim gelişimi, patatesin il ürün deseni içerisindeki konumunun ayrıca değerlendirilmesini gerekli kılmaktadır.

Nitekim 2020-2024 döneminde patates, incelenen ürünler içerisinde ekiliş alanı ve üretim miktarı bakımından en belirgin gelişmelerden birini göstermiştir. Sivas'taki ekiliş alanı beş yıllık dönemde iki katın üzerine çıkarken üretim miktarı da 192.630 tondan 560.398 tona ulaşmıştır. Bu gelişmeyle birlikte Sivas'ın Türkiye patates üretimindeki payı %3,70'ten %8,12'ye yükselmiştir (Çizelge 2). Üretimdeki gelişim yalnızca alan genişlemesiyle sınırlı kalmamış, özellikle 2022 ve 2023 yıllarında verimde de belirgin artış meydana gelmiştir. Sivas'ta patates verimi 2023 yılında 4.567 kg/da ile dönem içerisindeki en yüksek seviyeye ulaşmış, 2024 yılında ise 4.000 kg/da'a gerilemiştir. 2022-2023 dönemindeki gelişimde ekiliş alanındaki genişleme ile üretim tekniklerindeki iyileşmeler birlikte etkili olurken, 2024 yılındaki hızlı alan artışı patates verimi üzerinde kısa vadeli bir baskı oluşturmuştur.

Çizelge 2. Sivas ili patates üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	65.873	4,45	192.630	3,70	3.514	2.924
2021	71.180	5,12	194.742	3,82	3.671	2.736
2022	86.490	6,21	334.435	6,43	3.736	3.867
2023	89.862	5,95	410.377	7,20	3.777	4.567
2024	140.108	7,16	560.398	8,12	3.524	4.000

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Ayçiçeği (*Helianthus annuus* L.) Üretimi

Ayçiçeği, dünya bitkisel yağ sektörünün temel yağlı tohum ürünlerinden biri olup yağ üretiminin yanı sıra işleme sonucunda elde edilen küspenin hayvan beslemede kullanılabilmesi nedeniyle çok yönlü bir tarımsal üründür (Pilorgé, 2020). Türkiye'de ayçiçeği bitkisel yağ üretimi açısından stratejik öneme sahip ürünler arasında bulunmakta ve üretim alanı, verimlilik ve tarım politikaları bakımından önemini korumaktadır (Angın vd., 2025). Sivas'ta yağlık ayçiçeği yetiştiriciliğinin üretici düzeyinde doğrudan araştırmalara konu olması da ürünün bölgede giderek önem kazandığını göstermektedir (Yemen ve Belgüzar, 2024). Bu durum, ayçiçeğinin Sivas ürün desenindeki konumunun son yıllardaki ekiliş alanı, üretim ve verim değişimleri üzerinden değerlendirilmesini önemli hâle getirmektedir.

Bu doğrultuda 2020-2024 dönemindeki üretim seyri incelendiğinde ayçiçeğinde özellikle 2021-2023 döneminde hızlı bir genişleme meydana gelmiştir. Ekiliş alanı 2020 yılında 2.394 dekar düzeyindeyken 2022 yılında 83.337 dekara ulaşmış, üretim miktarı ise 2023 yılında 22.452 tonla dönem içerisindeki en yüksek seviyesine çıkmıştır. Buna paralel olarak Sivas'ın Türkiye ayçiçeği üretimindeki payı 2023 yılında %1,02'ye kadar yükselmiştir. 2024 yılında ise hem alan hem de üretim miktarında kısmi bir gerileme görülmüştür (Çizelge 3). Ekiliş alanındaki dalgalanmaya karşılık yağlık ayçiçeğinde verim dönem boyunca yükselmiş ve 2024 yılında 293 kg/da'a ulaşmıştır. Çerezlik ayçiçeğinde ise 2023 yılında 232 kg/da ile en yüksek değer elde edilmiş, 2024 yılında 198 kg/da'a gerilemiştir. Bu yapı, ayçiçeğinin Sivas'taki üretim desenine kısa sürede daha belirgin biçimde dahil olduğunu, ancak son yıldaki alan ve üretim gerilemesinin üretim eğiliminin sürekliliği bakımından izlenmesi gerektiğini göstermektedir.

Çizelge 3. Sivas ili ayçiçeği üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Yağlık verim (kg/da)	Çerezlik verim (kg/da)
2020	2.394	0,03	467	0,02	284	195	122
2021	14.000	0,16	2.796	0,12	268	200	129
2022	83.337	0,85	20.272	0,79	260	243	201
2023	81.516	0,86	22.452	1,02	231	275	232
2024	63.893	0,66	18.715	0,85	225	293	198

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

YEM BİTKİLERİ

Sivas'ta hayvancılığın yaygın olması, yem bitkilerinin üretim deseni içerisindeki önemini artırmaktadır. Bu çalışmada yem bitkileri içerisinde yonca ve silajlık mısır ele alınmıştır. İki ürün farklı üretim eğilimlerine sahip olmakla birlikte kaliteli kaba yem sağlanması bakımından hayvansal üretimle doğrudan ilişkilidir.

Yonca (*Medicago sativa* L.) Üretimi

Yonca, yüksek kaliteli kaba yem üretimi, çok yıllık yapısı ve baklagil özelliği nedeniyle dünya genelinde önemli yem bitkilerinden biridir. Tarımsal üretim sistemlerinde yem kaynağı oluşturmasının yanı sıra ekim nöbeti, azot fiksasyonu ve tarımsal ekosistem üzerindeki olumlu etkileri bakımından da değerlendirilmektedir (del Portillo vd., 2022). Türkiye'de yonca, silajlık mısır, yulaf, fiğ ve korungayla birlikte temel yem bitkileri arasında yer almakta ve kaliteli kaba yem üretimi açısından önem taşımaktadır (Tan ve Yolcu, 2021). Sivas ekolojik koşullarında farklı yonca çeşitleri üzerinde yürütülen çalışmalar da ürünün bölgede yüksek ve kaliteli ot üretimi potansiyeline sahip olduğunu göstermiştir (Karaköy ve Saraç, 2018). Yoncanın hayvansal üretim açısından taşıdığı bu önem, Sivas'taki ekiliş alanı, toplam üretim ve verim değişimlerinin birlikte değerlendirilmesini gerekli kılmaktadır.

Bu kapsamda 2020-2024 dönemi incelendiğinde, yonca ekiliş alanı 2022 yılına kadar sınırlı ölçüde artmış, daha sonra azalarak 2024 yılında 226.160 dekara gerilemiştir. Üretim miktarı da dönem sonunda 2020 düzeyinin altında kalmıştır. Buna karşılık Sivas'ın Türkiye toplam yonca ekiliş alanındaki payı %3,75'ten %4,03'e yükselmiş ve üretimdeki payı yaklaşık %1 düzeyinde korunmuştur (Çizelge 4). Verim 2021 yılında 674 kg/da'a gerilemiş, izleyen yıllarda düzenli biçimde artarak 2024 yılında 786 kg/da düzeyine ulaşmıştır. Tarımsal tekniklerin yanı sıra sulama ve gübreleme yönetimi verimliliği destekleyen uygulamalar arasında yer almaktadır. Buna karşılık su kısıtı bulunan alanlarda ekilişin azalması ve destekleme politikalarındaki değişiklikler üretim alanındaki daralmayı hızlandıran unsurlar arasında değerlendirilmiştir.

Çizelge 4. Sivas ili yonca üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	248.850	3,75	197.630	1,02	2.923	794
2021	255.176	3,79	171.933	0,89	2.895	674
2022	258.699	4,02	186.501	0,98	2.974	721
2023	248.190	4,13	184.872	1,01	3.056	745
2024	226.160	4,03	177.726	1,02	3.105	786

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Silajlık Mısır (*Zea mays* L.) Üretimi

Silajlık mısır, yüksek biyokütle üretimi ve enerji değeri nedeniyle özellikle süt sığırı beslemesinde yaygın olarak kullanılan önemli kaba yem kaynaklarından biridir. Bütün bitki mısır silajı, süt sığırı rasyonlarında önemli bir yem bileşeni olup hasat zamanı ve silaj kalitesi hayvanların yem tüketimi ve üretim performansını etkileyebilmektedir (Ferraretto vd., 2018). Türkiye'de de silajlık mısır kaliteli kaba yem üretimi bakımından önem kazanmış ve hayvancılıkla ilişkili başlıca yem bitkilerinden biri hâline gelmiştir (Karadeniz, 2019; Tan ve Yolcu, 2021). Sivas'ta hayvancılığın yaygın olması ve silajlık mısırın özellikle sulama imkânı bulunan tarım arazilerinde yetiştirilmesi, ürünü ilin yem bitkileri üretimi

açısından önemli hâle getirmektedir. Bu özellikler, silajlık mısırın Sivas'taki üretim gelişiminin ekiliş alanı, toplam üretim ve birim alan verimi bakımından birlikte ele alınmasını önemli kılmaktadır.
2020-2024 dönemindeki üretim seyri değerlendirildiğinde silajlık mısırda ekiliş alanı ve üretim miktarı 2020'den 2022'ye kadar artmış ve her iki gösterge de 2022 yılında dönem içerisindeki en yüksek seviyesine ulaşmıştır. Sonraki iki yılda alan ve üretimde kısmi bir gerileme görülmesine rağmen 2024 değerleri 2020 düzeyinin üzerinde kalmıştır. Sivas'ın Türkiye üretimindeki payı da %0,35'ten %0,45'e yükselmiştir (Çizelge 5). Alan ve toplam üretimde 2022 sonrasında görülen gerilemenin aksine birim alan verimi yükselmeye devam etmiş ve 2024 yılında 4.940 kg/da ile beş yıllık dönemin en yüksek değerine ulaşmıştır. Sulama ve gübreleme yönetimi verim artışını destekleyen uygulamalar arasında yer almaktadır. Silajlık mısırın özellikle sulama imkânı bulunan alanlarda yetiştirilmesi nedeniyle su kısıtı bulunan bölgelerde üretim alanının genişlemesi sınırlanabilmektedir.

Çizelge 5. Sivas ili silajlık mısır üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	20.484	0,39	94.473	0,35	5.226	4.612
2021	29.370	0,55	133.555	0,49	5.208	4.547
2022	31.458	0,59	149.251	0,52	5.444	4.744
2023	28.076	0,53	134.363	0,47	5.467	4.786
2024	24.893	0,49	122.973	0,45	5.424	4.940

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

YEMEKLİK DANE BAKLAGİLLER

Sivas, geniş tarım arazileri ve karasal iklim yapısıyla Türkiye'nin en önemli bitkisel üretim merkezlerinden biridir. Kentte yemeklik dane baklagil üretimi hem bölge ekonomisi hem de toprak yapısının korunması açısından stratejik bir öneme sahiptir

Kuru Fasulye (*Phaseolus vulgaris* L.) Üretimi

Kuru fasulye, doğrudan insan tüketiminde kullanılan en önemli baklagil türlerinden biri olup protein, diyet lifi ve mineral maddeler bakımından zengin bir besin kaynağıdır. Aynı zamanda baklagil özelliği, kısa yetişme süresi ve ekim nöbetlerinde kullanılabilmesi nedeniyle sürdürülebilir tarımsal üretim açısından da önem taşımaktadır (Uebersax vd., 2023). Türkiye'de kuru fasulye üretimi, tüketim ve pazarlama yapısı bakımından yemeklik tane baklagiller içerisinde önemli bir yere sahip olmakla birlikte üretim alanı ve miktarı yıllar içerisinde değişkenlik gösterebilmektedir (Küzeci vd., 2019). Sivas'ta ise üretim daha sınırlı düzeyde olmakla birlikte 2020-2024 döneminde ekiliş alanı, üretim ve verim değerlerindeki değişimler ürünün il üretim deseni içerisindeki gelişiminin izlenmesini gerekli kılmaktadır.
Bu doğrultuda 2020-2024 dönemi incelendiğinde, kuru fasulye üretimi dönem boyunca düzenli bir artış göstermemiştir. Ekiliş alanı 2022 yılında 6.770 dekarla en yüksek seviyesine ulaşırken, aynı yıl üretim miktarı da 946 tonla dönem içerisindeki en yüksek değeri göstermiştir. İzleyen yıllarda hem alan hem de üretim azalmış ve 2024 yılında sırasıyla 4.910 dekar ve 699 ton olarak gerçekleşmiştir (Çizelge 6). Verim bakımından ise farklı bir seyir ortaya çıkmış; 2021 yılında 98 kg/da'a gerileyen verim 2023 yılında 157 kg/da ile dönem içerisindeki en yüksek seviyesine ulaşmış ve 2024 yılında 142 kg/da olarak gerçekleşmiştir. Buna rağmen Sivas'taki verim değerleri incelenen yılların tamamında Türkiye ortalamasının altında kalmıştır. Üretim tekniklerindeki iyileşmeler, girdi kullanımındaki etkinlik ve uygun iklim koşulları verimdeki gelişmeyle ilişkilendirilen unsurlar arasında yer almaktadır.

Çizelge 6. Sivas ili kuru fasulye üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	3.151	0,31	338	0,12	271	107
2021	4.068	0,38	399	0,13	283	98

2022	6.770	0,70	946	0,35	278	140
2023	5.408	0,61	849	0,35	271	157
2024	4.910	0,53	699	0,25	304	142

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

GENEL DEĞERLENDİRME VE SONUÇ

Sivas'ta 2020-2024 döneminde incelenen ürünler birlikte değerlendirildiğinde, farklı ürün gruplarının ekiliş alanı, üretim miktarı ve verim bakımından birbirinden farklı gelişim eğilimlerine sahip olduğu görülmektedir.

Endüstriyel üretimle ilişkili şeker pancarı dönem boyunca görece istikrarlı bir alan ve üretim yapısı gösterirken, patateste belirgin bir genişleme meydana gelmiştir. Patatesin hem ekiliş alanındaki hem de Türkiye toplam üretimindeki payındaki artış, ürünün Sivas bitkisel üretimindeki göreli ağırlığının dönem içerisinde yükseldiğini göstermektedir. Ayçiçeğinde ise daha hızlı ancak daha değişken bir gelişim görülmüştür. Ekiliş alanı ve üretim miktarının kısa süre içerisinde önemli ölçüde artmasının ardından 2024 yılında her iki göstergede de kısmi bir gerileme meydana gelmiştir. Buna karşılık yağlık ayçiçeğinde verimin dönem boyunca yükselmesi, üretim alanı ile birim alan veriminin her zaman aynı yönde değişmediğini ortaya koymaktadır. Yem bitkilerinde de benzer biçimde ürün bazında farklı eğilimler bulunmaktadır. Yonca ekiliş alanı ve toplam üretim miktarı dönem sonunda azalmasına rağmen verim 2021 yılından sonra yeniden yükselmiştir. Silajlık mısırda ekiliş alanı ve üretim 2022 yılında en yüksek düzeye ulaştıktan sonra kısmen gerilemiş, buna karşılık birim alan verimi yükselmeye devam ederek 2024 yılında dönem içerisindeki en yüksek değerine ulaşmıştır. Bu durum, yem bitkilerinde toplam üretimin yalnızca verim değişimiyle değil, üretim alanındaki gelişmelerle birlikte değerlendirilmesi gerektiğini göstermektedir. Kuru fasulyede ise ekiliş alanı ve üretim miktarında sürekli bir genişleme eğilimi ortaya çıkmamış; her iki gösterge 2022 yılında en yüksek düzeye ulaştıktan sonra gerilemiştir. Bununla birlikte verim değerlerinin 2022 sonrasında önceki iki yıla göre daha yüksek gerçekleşmesi, alan ve verim değişimlerinin farklı yönlerde gelişebildiğini göstermektedir.

Genel olarak Sivas'ta incelenen ürünler arasında şeker pancarı gibi görece istikrarlı bir üretim yapısına sahip ürünler ile patates ve ayçiçeği gibi daha belirgin alan değişimleri gösteren ürünler birlikte bulunmaktadır. Yonca, silajlık mısır ve kuru fasulyede ise üretim alanı, toplam üretim ve verim göstergelerinin farklı yönlerde geliştiği görülmektedir. Bu nedenle Sivas'taki üretim deseninin planlanmasında ekiliş alanı, birim alan verimi, yıllar arasındaki üretim değişkenliği ve ürünlerin su gereksinimlerinin birlikte değerlendirilmesi önem taşımaktadır.

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MULTI-OBJECTIVE OPTIMIZATION OF PHOTOVOLTAIC SYSTEM ORIENTATION CONSIDERING ADJUSTMENT EFFORT INDEX

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Abstract
This study presents a multi-objective optimization framework for determining monthly photovoltaic (PV) panel orientations while considering both solar irradiation capture and the practical effort required for orientation adjustments. Two strategies are investigated: joint optimization of monthly tilt and azimuth angles and tilt-only optimization with the azimuth fixed at 0° (south-facing). Annual plane-of-array (POA) irradiation is maximized, while orientation adjustment effort is minimized through a proposed Adjustment Effort Index (AEI), which accounts for both the number of interventions and cumulative angular movements. The analysis is performed using measured global, diffuse, and beam horizontal irradiance data obtained from the Renewable Energy Research Home at Eskişehir Technical University, Türkiye. A multi-objective genetic algorithm is employed to obtain the Pareto-optimal orientation schedules, and the two strategies are evaluated using maximum-irradiation solutions, compromise solutions, and equal-AEI comparisons. The joint tilt-azimuth strategy achieved a maximum annual POA irradiation of 1841.82 kWh/m², compared with 1796.97 kWh/m² for tilt-only optimization, corresponding to a 2.50% improvement. For the selected compromise solutions, joint optimization increased annual POA irradiation from 1790.97 to 1825.01 kWh/m² (1.90%), while both strategies required six orientation interventions. Moreover, cumulative tilt movement decreased from 68° to 29° by distributing the orientation changes between tilt and azimuth. The results demonstrate that incorporating azimuth flexibility can improve solar irradiation capture without necessarily increasing the overall adjustment effort, providing a practical basis for periodically adjustable PV systems.
Keywords: Photovoltaic systems, tilt angle, azimuth angle, multi-objective optimization, solar irradiance, adjustment effort.

Introduction

Background

Photovoltaic (PV) systems have become an increasingly important component of sustainable electricity generation. In addition to module characteristics and environmental conditions, PV array orientation directly affects the solar irradiance received by the module surface and consequently its energy-generation potential. The orientation is primarily determined by the tilt and azimuth angles, while the optimal values of these angles vary throughout the year due to changes in solar geometry. Therefore, appropriately selecting PV orientation can improve solar energy utilization without increasing the installed PV capacity.

Fixed-orientation PV systems are simple and require no operational intervention; however, a single annual orientation cannot continuously provide favourable irradiation conditions throughout the year. Periodic adjustment of the panel orientation, such as monthly or seasonal reorientation, provides an intermediate alternative between fixed installations and continuously operating solar tracking systems. Nevertheless, maximizing irradiation through frequent orientation changes may require considerable operational or mechanical effort, particularly when both tilt and azimuth angles are adjustable.

Most PV orientation optimization studies primarily aim to maximize incident solar irradiation or energy production. However, the practical effort associated with transitioning between successive orientations is generally not explicitly considered as an optimization objective. The number of adjustments alone cannot fully represent this effort, since schedules having the same number of interventions may involve considerably different angular displacements. Therefore, PV orientation optimization should consider not only the attainable irradiation but also the frequency and magnitude of the required orientation changes.

In this study, a multi-objective framework is proposed to simultaneously maximize annual plane-of-array (POA) irradiation and minimize orientation adjustment effort. An Adjustment Effort Index (AEI)

is formulated by considering the number of orientation interventions together with cumulative tilt and azimuth movements. Two strategies are investigated: joint monthly optimization of tilt and azimuth angles and monthly tilt-only optimization with the azimuth fixed at 0° (south-facing). Their Pareto fronts, compromise solutions, and performance under equal AEI constraints are compared to quantify the additional benefit provided by azimuth flexibility.

The analysis is conducted using measured global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), and beam horizontal irradiance (BHI) data obtained from the Renewable Energy Research Home (RERH) at the Iki Eylul Campus of Eskişehir Technical University, Eskişehir, Türkiye. The main contribution of the study is therefore a practical multi-objective PV orientation methodology that explicitly incorporates both irradiation gain and orientation-adjustment effort, enabling the additional value of azimuth optimization to be evaluated under equivalent operational-effort conditions.

Literature Review

The orientation of a PV panel strongly influences the amount of solar irradiation received by its surface. Early studies therefore focused on determining optimum tilt and orientation angles for different locations and operating periods. Ibrahim investigated south-facing solar collectors in Cyprus and showed that near-optimal solar energy collection could be achieved by adjusting the tilt angle four times per year (Ibrahim, 1995). Bari developed a computational procedure for determining both the optimum slope and orientation of solar collectors for different periods of utilization while considering direct and diffuse solar radiation (Bari, 2000). Similarly, Yakup and Malik optimized both tilt and surface azimuth angles for Brunei Darussalam and reported that monthly tilt adjustment could provide annual solar irradiation close to that obtained through daily optimum adjustment (Yakup & Malik, 2001).

Location-specific studies have also demonstrated that optimum PV orientation cannot be determined accurately using latitude alone. Kacira et al. determined optimum PV tilt angles for Şanlıurfa, Türkiye, and reported monthly values ranging from 13° in June to 61° in December. They also showed that monthly optimum tilt angles increased the received solar radiation compared with seasonal and latitude-based configurations (Kacira et al., 2004). Tang and Wu emphasized that the optimum tilt angle depends on local climatic conditions, geographic latitude, and the period of utilization (Tang & Wu, 2004). For Türkiye, Bakirci used measured solar radiation data from eight provinces and demonstrated substantial seasonal variation in optimum tilt angles (Bakirci, 2012). These findings are also consistent with the comprehensive review by Yadav and Chandel, who concluded that optimum tilt is both site- and time-dependent and should therefore be determined using appropriate radiation models and optimization techniques (Yadav & Chandel, 2013).

The use of tracking systems provides an alternative means of increasing irradiation capture by continuously or periodically modifying panel orientation. Koussa et al. compared fixed PV configurations with several single- and two-axis tracking systems using hourly measured data under different sky conditions and demonstrated that tracking can significantly increase energy yield, although the achieved gains depend strongly on environmental conditions (Koussa et al., 2011). A broader review of tilt, azimuth, and tracking strategies was presented by Hafez et al., confirming that both tilt and azimuth optimization have been extensively studied for different solar-energy applications (Hafez et al., 2017). However, tracking systems generally involve additional mechanical components, operational energy requirements, and maintenance costs. For this reason, periodically adjustable PV structures can provide a practical compromise between completely fixed systems and continuously operating tracking systems.

The trade-off between energy gain and adjustment frequency has therefore received increasing attention. Despotovic and Nedic compared yearly, biannual, seasonal, monthly, fortnightly, and daily optimum tilt schedules and showed that increasing the frequency of adjustment does not necessarily result in proportional increases in collected energy. They also reported relatively small differences among daily, fortnightly, and monthly optimum configurations and emphasized the importance of cost-benefit considerations (Despotovic & Nedic, 2015). More recently, Prunier et al. proposed a bi-layer optimization approach that determines both optimum tilt angles and the dates of panel reorientation. Their results indicated that two reorientations per year could improve annual energy production by up to 4.8%, whereas further increases in the number of adjustments provided progressively smaller additional gains (Prunier et al., 2023).

Recent studies have also adopted more detailed radiation datasets and data-driven optimization approaches. Inan et al. determined annual, seasonal, and monthly optimum tilt angles for seven cities in Türkiye using PVGIS data and reported energy gains of up to 4.20% and 5.05% for seasonal and monthly adjustment, respectively (Inan et al., 2024). Lu and Qin used long-term hourly solar radiation data to determine location-specific optimum PV tilt angles across China and showed that the optimum angle is sensitive to both regional climate variability and the time period considered in the optimization (Lu & Qin, 2024).

Despite these developments, the reviewed studies predominantly focus on maximizing solar irradiation or energy production, while the practical effort associated with panel reorientation is generally represented indirectly through predefined adjustment frequencies. Although several studies acknowledge the practical and economic implications of reorientation (Yakup & Malik, 2001; Despotovic & Nedic, 2015) and recent work has optimized the timing of tilt adjustments (Prunier et al., 2023), the reviewed literature does not explicitly formulate adjustment effort as a competing optimization objective that simultaneously considers both the number of interventions and cumulative angular displacement. Furthermore, a direct comparison between joint tilt-azimuth optimization and tilt-only optimization under equivalent adjustment-effort conditions has not been addressed within the reviewed studies. Therefore, the present study introduces an AEI and formulates PV orientation as a multi-objective optimization problem in which annual plane-of-array irradiation is maximized while orientation adjustment effort is minimized.

Mathematical Formulation

Problem Definition

The PV orientation problem is formulated as a bi-objective optimization problem in which the annual POA irradiation is maximized while the practical effort associated with panel orientation is minimized. Two monthly orientation strategies are considered. In the first strategy, monthly tilt and azimuth angles are jointly optimized, with separate decision variables assigned to each month. In the second strategy, only the monthly tilt angles are optimized while the azimuth angle is maintained at 0°, corresponding to a south-facing orientation.

For month m, β_m and γ_m denote the PV tilt and azimuth angles, respectively. For the joint tilt-azimuth optimization case, the decision vector is

$$\mathbf{x}_{TA} = [\beta_1, \dots, \beta_{12}, \gamma_1, \dots, \gamma_{12}]. \quad (1)$$

For the tilt-only optimization case, the decision vector is

$$\mathbf{x}_T = [\beta_1, \dots, \beta_{12}]. \quad (2)$$

while

$$\gamma_m = 0°, m = 1, \dots, 12. \quad (3)$$

The orientation variables are constrained by

$$0° \leq \beta_m \leq 90°, m = 1, \dots, 12. \quad (4)$$

and for the joint tilt-azimuth case,

$$-180° \leq \gamma_m \leq 180°, m = 1, \dots, 12. \quad (5)$$

A 1° angular resolution is adopted. The azimuth convention is defined such that $\gamma = 0°$ represents south, negative values represent eastward orientations, and positive values represent westward orientations.

Solar Geometry Model

The solar declination angle at hourly time step t is calculated as (Barbón et al., 2022; Sunderan et al., 2011)

$$\delta(t) = 23.45° sin\left[\frac{360°(284+n(t))}{365}\right]. \quad (6)$$

where $n(t)$ denotes the day of the year.

The auxiliary parameter used in the equation-of-time calculations is

$$B(t) = \frac{360°}{365}[n(t) - 81]. \quad (7)$$

The equation of time is expressed as

$$EoT(t) = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B). \quad (8)$$

The time correction factor is

$$TC(t) = EoT(t) + 4(\lambda - \lambda_{std}). \quad (9)$$

where λ denotes the longitude of the study location and λ_{std} is the standard longitude corresponding to the local time zone.
The solar time is calculated as
$$ST(t) = LT(t) + \frac{TC(t)}{60}. \quad (10)$$
where $LT(t)$ represents the local clock time. The corresponding solar hour angle is
$$\omega(t) = 15°[ST(t) - 12]. \quad (11)$$
The cosine of the solar zenith angle is determined as
$$cos\theta_z(t) = sin\varphi sin\delta(t) + cos\varphi cos\delta(t) cos\omega(t). \quad (12)$$
where φ denotes the latitude of the study location. The direct normal irradiance (DNI) is obtained from the beam horizontal irradiance (BHI) according to
$$DNI(t) = \frac{BHI(t)}{cos\theta_z(t)}. \quad (13)$$
for periods during which the sun is above the horizon.

Plane-of-Array Irradiance (POA) Model
For a PV surface having the tilt angle β and the azimuth angle γ, the cosine of the incidence angle is calculated as (Barbón et al., 2022; Sunderan et al., 2011)
$$cos\theta_i(t) = sin\delta(t) sin\varphi cos\beta - sin\delta(t) cos\varphi sin\beta cos\gamma + cos\delta(t) cos\varphi cos\beta cos\omega(t) + cos\delta(t) sin\varphi sin\beta cos\gamma cos\omega(t) + cos\delta(t) sin\beta sin\gamma sin\omega(t). \quad (14)$$
Only positive incidence-angle contributions are considered, such that
$$cos\theta_i(t) = \max[cos\theta_i(t), 0]. \quad (15)$$
The beam component incident on the tilted PV surface is
$$G_{b,POA}(t) = DNI(t) cos\theta_i(t). \quad (16)$$
Using the isotropic diffuse-sky model, the diffuse component is
$$G_{d,POA}(t) = DHI(t) \frac{1+cos\beta}{2}. \quad (17)$$
where $DHI(t)$ denotes diffuse horizontal irradiance. The ground-reflected component is calculated as
$$G_{r,POA}(t) = \rho_g GHI(t) \frac{1-cos\beta}{2}. \quad (18)$$
where ρ_g is the ground reflectance and $GHI(t)$ represents global horizontal irradiance. The total POA irradiance is therefore given by
$$G_{POA}(t, \beta, \gamma) = G_{b,POA}(t) + G_{d,POA}(t) + G_{r,POA}(t). \quad (19)$$

Maximization of Annual POA Irradiation
The first objective function considered in this study is the maximization of annual POA irradiation. Let τ_m denote the set of hourly observations belonging to month m. Since one orientation is used throughout each month, the monthly POA irradiation is computed by
$$H_m(\beta_m, \gamma_m) = \sum_{t \in \tau_m} G_{POA}(t, \beta_m, \gamma_m) \Delta t. \quad (20)$$
where $\Delta t = 1\ h$ for the hourly dataset. The total annual POA irradiation is
$$H_{annual} = \sum_{m=1}^{12} H_m(\beta_m, \gamma_m). \quad (21)$$
For the joint tilt-azimuth case,
$$H_{TA} = \sum_{m=1}^{12} H_m(\beta_m, \gamma_m). \quad (22)$$
whereas for the tilt-only case,
$$H_T = \sum_{m=1}^{12} H_m(\beta_m, 0°). \quad (23)$$
The first objective function of both optimization problems is therefore expressed by
$$\max f_1 = H_{annual}. \quad (24)$$

Adjustment Effort Index
The second objective function is used to quantify the practical burden associated with changing the PV orientation. The absolute change in tilt angle between two consecutive months is defined as
$$\Delta\beta_m = |\beta_m - \beta_{m-1}|, m = 2, \dots, 12. \quad (25)$$
Since azimuth is a circular variable, the physical azimuth displacement is calculated using the shortest angular distance,
$$\Delta\gamma_m = \min[|\gamma_m - \gamma_{m-1}|, 360° - |\gamma_m - \gamma_{m-1}|]. \quad (26)$$
Accordingly,

$0° \leq \Delta\gamma_m \leq 180°.$ (27)

An orientation-adjustment indicator is defined as

$$u_m = \begin{cases} 1, & \Delta\beta_m + \Delta\gamma_m > 0 \\ 0, & otherwise \end{cases}. \quad (28)$$

The annual number of orientation adjustments is

$N_{adj} = \sum_{m=2}^{12} u_m.$ (29)

With monthly orientation scheduling, at most 11 month-to-month transitions can occur. Therefore, the normalized adjustment-frequency component is

$I_N = \frac{N_{adj}}{11}.$ (30)

Since the maximum possible tilt displacement during one transition is 90°, the normalized cumulative tilt movement is

$I_\beta = \frac{\sum_{m=2}^{12} \Delta\beta_m}{11\times 90°}.$ (31)

Similarly, since the maximum azimuth displacement during one transition is 180°, the normalized cumulative azimuth movement is

$I_\gamma = \frac{\sum_{m=2}^{12} \Delta\gamma_m}{11\times 180°}.$ (32)

A common AEI formulation is employed for both orientation strategies:

$AEI = \omega_N I_N + \omega_\beta I_\beta + \omega_\gamma I_\gamma.$ (33)

where ω_N, ω_β, and ω_γ denote the weighting coefficients associated with adjustment frequency, cumulative tilt movement, and cumulative azimuth movement, respectively. For the tilt-only case, the azimuth angle remains constant and hence $I_\gamma = 0$.

Equal weighting is adopted for the baseline analysis,

$\omega_N = \omega_\beta = \omega_\gamma = 1.$ (34)

The second objective is therefore expressed as

$\min f_2 = AEI.$ (35)

Multi-Objective Formulation

For the joint tilt-azimuth strategy, the optimization problem is

$$\max_{\mathbf{x}_{TA}} H_{TA}$$
$$\min_{\mathbf{x}_{TA}} AEI_{TA}. \quad (36)$$

subject to

$0° \leq \beta_m \leq 90°\ , -180° \leq \gamma_m \leq 180°.$ (37)

For the tilt-only strategy,

$$\max_{\mathbf{x}_T} H_T$$
$$\min_{\mathbf{x}_T} AEI_T. \quad (38)$$

subject to

$0° \leq \beta_m \leq 90°\ , \gamma_m = 0°.$ (39)

To enforce the adopted 1° angular resolution, candidate orientation variables generated during the optimization are rounded to the nearest integer before evaluation using the monthly POA lookup table.

Methodology

Monthly POA Lookup Table

Direct calculation of hourly POA irradiation for every candidate individual generated during the optimization process would require a large number of repeated solar-geometry calculations. Therefore, a preprocessing procedure is employed as described below. The POA irradiation is evaluated for all integer combinations within

$\beta \in \{0°, 1°, \dots, 90°\}, \gamma \in \{-180°, -179°, \dots, 180°\}$ (40)

For each (β, γ) pair, the hourly POA values are calculated using Eq. (19). These hourly values are then aggregated separately for every month, resulting in the lookup table.

$H_m(\beta, \gamma), m = 1, \dots, 12.$ (41)

For any candidate monthly orientation schedule, annual irradiation can therefore be obtained directly for tilt-azimuth and tilt-only cases as given in Eqs. (22) and (23), respectively.

Multi-Objective Optimization

The multi-objective optimization problems are solved using the controlled elitist multi-objective genetic algorithm implemented in MATLAB (MathWorks, 2024). The tilt-only problem is first solved to obtain its Pareto-optimal candidate solutions. For the larger joint tilt-azimuth search space, both unseeded and partially seeded optimization runs are performed to preserve global exploration while improving the representation of low-adjustment-effort regions. The tilt-only Pareto solutions are additionally embedded in the joint feasible space by setting all azimuth angles to 0°. The resulting candidate solutions are merged and subjected to non-dominated filtering to obtain the final joint Pareto front. The joint tilt-azimuth problem contains 24 decision variables, whereas the tilt-only optimization contains 12 decision variables. Candidate orientation schedules are evaluated using the two objective functions defined by $\mathbf{F}_{TA} = [-H_{TA}, AEI_{TA}]$ and $\mathbf{F}_{T} = [-H_{T}, AEI_{T}]$. The negative signs are applied to H_{TA} and H_T to transform the maximization objectives to the minimization form. The optimization produces a set of non-dominated solutions rather than a single operating point. A solution x^A dominates another solution x^B if it is no worse than in both objectives and strictly better in at least one objective. The set of non-dominated solutions constitutes the Pareto-optimal set. Each Pareto solution therefore represents a different compromise between annual POA and adjustment effort.

Compromise Solution Selection

A representative compromise operating point is determined from each Pareto front using normalization and Euclidean distance to an ideal point. The annual POA irradiation of solution i is normalized as

$$H_{norm,i} = \frac{H_i - H_{min}}{H_{max} - H_{min}}. \quad (42)$$

The corresponding AEI is normalized according to

$$AEI_{norm,i} = \frac{AEI_i - AEI_{min}}{AEI_{max} - AEI_{min}}. \quad (43)$$

The normalized ideal point is $(H_{norm,}\, AEI_{norm,}) = (1, 0)$ representing simultaneous maximum irradiation and minimum adjustment effort. The Euclidean distance of Pareto solution i from the ideal point is

$$d_i = \sqrt{\left(1 - H_{norm,i}\right)^2 + AEI_{norm,i}^2}. \quad (44)$$

The representative compromise solution is then selected as

$$i^* = \underset{i}{\operatorname{argmin}}\, d_i. \quad (45)$$

Comparison Metrics

Maximum-Irradiation Benefit of Azimuth Optimization

The maximum achievable irradiation benefit obtained by allowing azimuth optimization is quantified as

$$\Delta H_{\gamma,max} = H_{TA,max} - H_{T,max}. \quad (46)$$

and its percentage value is given by

$$G_{\gamma,max} = \frac{H_{TA,max} - H_{T,max}}{H_{T,max}} \times 100. \quad (47)$$

The corresponding irradiation-retention ratio of the tilt-only strategy is defined as

$$R_{T,max} = \frac{H_{T,max}}{H_{TA,max}} \times 100. \quad (48)$$

Compromise Solution Comparison

For the independently selected compromise solutions, the irradiation difference is

$$\Delta H_{\gamma,c} = H_{TA,c} - H_{T,c}. \quad (49)$$

where the subscript c denotes the compromise solution. The percentage irradiation benefit of azimuth optimization is

$$G_{\gamma,c} = \frac{H_{TA,c} - H_{T,c}}{H_{T,c}} \times 100. \quad (50)$$

The irradiation-retention ratio of tilt-only optimization is

$$R_{T,c} = \frac{H_{T,c}}{H_{TA,c}} \times 100. \quad (51)$$

The compromise points are selected independently from their respective Pareto fronts and therefore do not necessarily correspond to identical AEI values. Consequently, differences between their AEI values are reported descriptively rather than used to construct a marginal irradiation-per-AEI indicator.

Equal-AEI Comparison

Since the two Pareto fronts are generated independently, their individual compromise points do not necessarily represent the same adjustment-effort level. Therefore, an equal-AEI comparison is used for a more direct evaluation. For a prescribed adjustment-effort budget AEI_b, the maximum achievable annual irradiation of the joint tilt-azimuth strategy is

$$H_{TA}^*(AEI_b) = \max_{\mathbf{x}_{TA}} \{H_{TA} : AEI_{TA} \le AEI_b\}. \quad (52)$$

Similarly, the maximum annual irradiation of the tilt-only strategy is

$$H_T^*(AEI_b) = \max_{\mathbf{x}_T} \{H_T : AEI_T \le AEI_b\}. \quad (53)$$

Feasible-Set Consistency

The tilt-only feasible set constitutes a subset of the joint tilt–azimuth feasible set. Specifically, every feasible tilt-only solution can be represented within the joint formulation by imposing

$$\gamma_1 = \gamma_2 = \cdots = \gamma_{12} = 0°. \quad (54)$$

For this embedded solution,

$$I_\gamma = 0. \quad (55)$$

and therefore, both its POA irradiation and AEI are identical to those of the corresponding tilt-only solution.

Consequently, for any common AEI budget AEI_b, the globally optimal solutions must satisfy

$$H_{TA}^*(AEI_b) \ge H_T^*(AEI_b) \quad (56)$$

Equation (56) provides an important consistency condition for the numerical optimization. If the numerically approximated tilt-azimuth Pareto front produces a lower irradiation than the tilt-only front under the same AEI budget, this does not represent a physical disadvantage of azimuth flexibility. Instead, it indicates that the larger joint search space has not been sufficiently sampled in that region of the Pareto front.

Azimuth Benefit Under Equal Adjustment Effort

The absolute irradiation benefit provided by azimuth flexibility at the same AEI budget is defined as

$$\Delta H_\gamma(AEI_b) = H_{TA}^*(AEI_b) - H_T^*(AEI_b). \quad (57)$$

The corresponding percentage benefit is

$$G_\gamma(AEI_b) = \frac{H_{TA}^*(AEI_b) - H_T^*(AEI_b)}{H_T^*(AEI_b)} \times 100. \quad (58)$$

For a sufficiently converged solution of the two optimization problems,

$$G_\gamma(AEI_b) \ge 0. \quad (59)$$

A zero value indicates that the additional azimuth degree of freedom provides no irradiation improvement at the considered adjustment budget, whereas a positive value quantifies the additional solar resource captured through azimuth flexibility.

The proposed formulation evaluates PV orientation through two conflicting objectives: maximizing annual POA irradiation and minimizing orientation-adjustment effort. A unified AEI is employed for both tilt–azimuth and tilt-only optimization, allowing the two strategies to be compared on a consistent basis. The tilt-only configuration is mathematically embedded within the joint tilt–azimuth formulation by fixing all azimuth angles to 0◦. This nested feasible-set relationship establishes an important theoretical condition: at an identical AEI budget, the joint optimization cannot provide lower globally optimal irradiation than the tilt-only configuration. Accordingly, the final comparison is performed using maximum-irradiation solutions, independently selected compromise solutions, cumulative orientation movements, and equal-AEI performance. This formulation enables the additional irradiation benefit of azimuth flexibility to be quantified while simultaneously considering the practical burden associated with panel reorientation.

Findings and Discussion

This section first presents the measured solar irradiance data used as the input to the optimization framework and then evaluates the resulting multi-objective PV orientation solutions. The hourly GHI, DHI, and BHI data obtained from the RERH at Eskişehir Technical University (Filik et al., 2018), as shown in Fig. 1, are followed by a comparative assessment of the tilt-azimuth and tilt-only strategies in terms of POA irradiation, AEI, Pareto performance, and optimal monthly orientation schedules.

Optimization Performance

The multi-objective optimization is performed for two orientation strategies. In the first case, both the tilt and azimuth angles are allowed to vary on a monthly basis, whereas in the second case only the tilt angle is optimized while the azimuth angle is fixed at 0°. The resulting solutions quantify the trade-off between POA irradiation and AEI. Table 1 summarizes the maximum-irradiation and compromise solutions obtained for the two strategies. The joint tilt-azimuth optimization achieves a maximum annual POA irradiation of 1841.8 kWh/m^2, compared with 1796.9 kWh/m^2 for the tilt-only strategy. Thus, incorporating azimuth as an additional decision variable increases maximum attainable irradiation by 44.9 kWh/m^2, corresponding to a relative improvement of 2.50%. Despite the restriction imposed by fixing the azimuth angle, the tilt-only configuration retains 97.6% of the maximum irradiation attainable through joint orientation optimization.

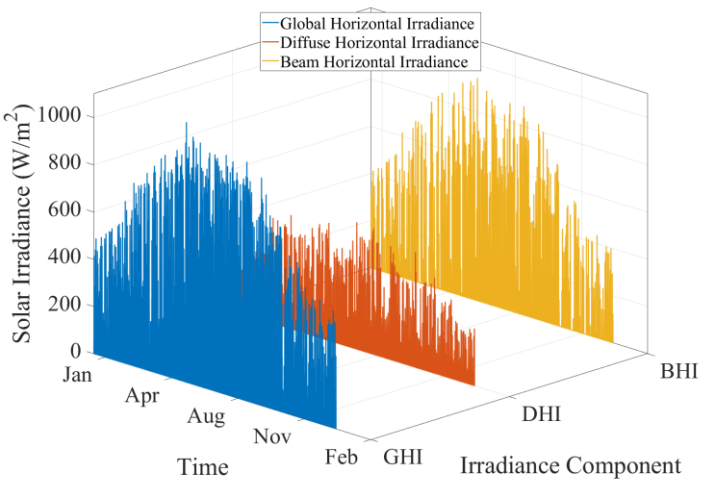


Figure 1. Hourly GHI, DHI, and BHI data obtained from the RERH at the Iki Eylul Campus of Eskişehir Technical University.

Table 1. Comparison of Two Optimization Strategies

Performance Indicator	Tilt-Azimuth	Tilt-Only
Maximum POA irradiation (kWh/m²)	1841.8	1796.9
AEI at maximum POA	1.0934	1.0919
Adjustments at maximum POA	11	11
Compromise POA irradiation (kWh/m²)	1825.0	1790.9
Compromise AEI	0.6061	0.6141
Compromise adjustments	6	6
Cumulative tilt movement (°)	29	68
Cumulative azimuth movement (°)	62	0

The maximum-irradiation solutions require 11 orientation adjustments in both cases, indicating that maximum solar-energy capture favors frequent orientation. However, the additional irradiation obtained by permitting azimuth adjustment is relatively modest compared with the increased mechanical flexibility required by a two-axis adjustable structure. Consequently, maximizing irradiation alone does not provide sufficient information for selecting an orientation strategy. This observation motivates the inclusion of adjustment effort as a second objective and the examination of the resulting Pareto-optimal solutions.

The minimum-AEI endpoint provides the opposite extreme. At $AEI = 0$, both optimization strategies yield exactly 1584.2 kWh/m^2. This equality is expected because zero adjustment effort eliminates the benefit of monthly reorientation and is consistent with the common zero-adjustment configurations available to both formulations.

Pareto Trade-Off Between Irradiation and Adjustment Effort

Fig. 2 presents the Pareto fronts obtained for the two optimization strategies. The figure clearly demonstrates the conflicting nature of the objectives: higher annual POA irradiation generally requires a higher AEI. The solutions are distributed from low-effort configurations with annual irradiation around 1584-1630 kWh/m^2 to more actively adjusted configurations approaching 1800 kWh/m^2 for tilt-only optimization and approximately 1842 kWh/m^2 when both orientation variables are optimized. The most important characteristic of Fig. 2 is that the joint tilt-azimuth formulation expands the achievable objective space. At very low adjustment effort, the two methods provide similar performance because there is insufficient adjustment freedom for the azimuth degree of freedom to provide a substantial benefit. As AEI increases, however, the joint optimization increasingly outperforms the tilt-only configuration. This indicates that azimuth flexibility becomes particularly beneficial when a moderate or high level of seasonal reorientation is permitted.

The discontinuous structure of the Pareto fronts stems from the fact that AEI contains a component associated with the number of orientation interventions; consequently, increasing the number of adjustments introduces discrete changes in the objective. The Pareto front therefore does not necessarily evolve as a smooth continuous curve. Instead, clusters of solutions occur for configurations having similar numbers of orientation interventions.

Comparison at Equal Adjustment Effort

A direct comparison of independently selected Pareto solutions may be misleading because the solutions can have different AEI values. Therefore, the two optimization strategies are additionally evaluated under identical maximum allowable AEI budgets. Fig. 3 presents the maximum achievable POA irradiation for each strategy as the AEI budget is progressively increased.

The equal-AEI comparison provides particularly strong evidence for the benefit of joint orientation optimization. At an AEI budget of approximately 0.11, the joint strategy produces 1598.2 kWh/m^2, whereas the tilt-only strategy produces 1588.9 kWh/m^2, corresponding to an improvement of approximately 0.585%. At an AEI of approximately 0.20, the respective values increase to 1616.5 and 1607.8 kWh/m^2.

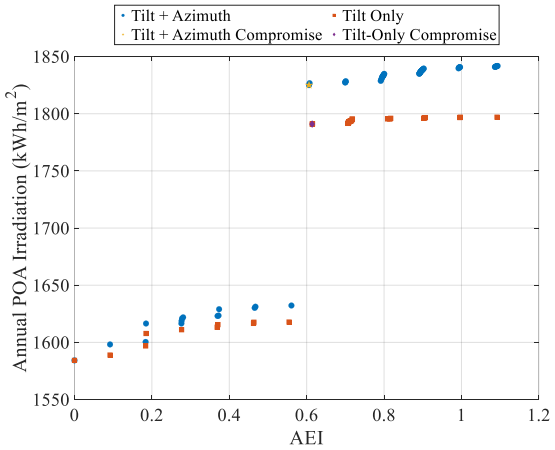


Figure 2. Pareto fronts of annual POA irradiation and AEI for the tilt-azimuth and tilt-only optimization strategies.

The benefit becomes considerably more pronounced as the allowable adjustment effort increases. For example, at an AEI of approximately 0.80, the joint optimization reaches 1834.9 kWh/m^2, compared with 1795.4 kWh/m^2 for tilt-only optimization, yielding an improvement of approximately 2.20%. At an AEI budget of 1.0919, the corresponding values are approximately 1841.7 and 1797.0 kWh/m^2, respectively, resulting in an improvement of approximately 2.49%.

Importantly, the numerical nested-feasible-set check confirms that $H_{TA}^{*}(AEI_b) \geq H_{T}^{*}(AEI_b)$ for every evaluated AEI budget where $H_{TA}^{*}(AEI_b)$ and $H_{T}^{*}(AEI_b)$ denote the best attainable irradiation for the joint tilt–azimuth and tilt-only strategies, respectively. Consistent with the nested feasible-set property, the best joint solution obtained at each evaluated AEI budget was never inferior to the corresponding tilt-only solution. Theoretically, this condition follows because every tilt-only schedule remains feasible within the joint formulation. This is an important practical result. It demonstrates that the benefit of azimuth optimization is not merely caused by permitting the two-axis system to perform more adjustments. Instead, even when the two systems are subjected to the same AEI constraint, the additional orientation degree of freedom allows the available adjustment effort to be allocated more effectively.

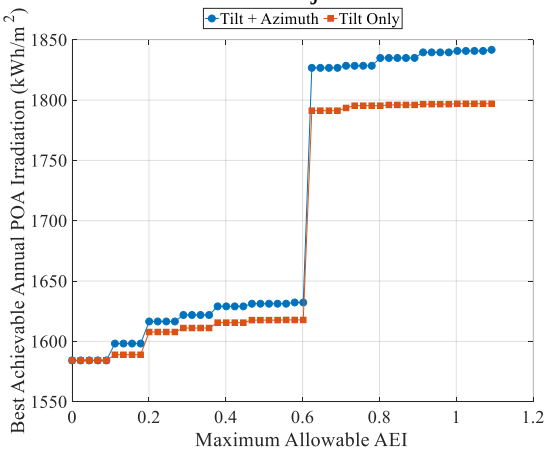


Figure 3. Best achievable annual POA irradiation under identical maximum allowable AEI values.

Relative Benefit of Azimuth Optimization

The irradiation advantage provided by azimuth optimization as a function of AEI is illustrated in Fig. 4. At very low AEI values, the advantage is essentially zero because both systems remain close to their low-adjustment configurations. Once adjustment effort is permitted, however, the benefit becomes positive and generally increases with AEI.

The relative benefit initially remains below approximately 1%, but increases substantially once the AEI approaches 0.6. The improvement subsequently reaches approximately 2.0%, exceeds 2.2% around an AEI of 0.80, and approaches 2.5% near the maximum investigated adjustment effort. This trend indicates that azimuth optimization becomes increasingly valuable as greater orientation flexibility is allowed. In other words, a system designed for almost fixed operation receives little benefit from adding azimuth adjustability, whereas a system intended for periodic manual or mechanical reorientation can exploit the second orientation degree of freedom more effectively.

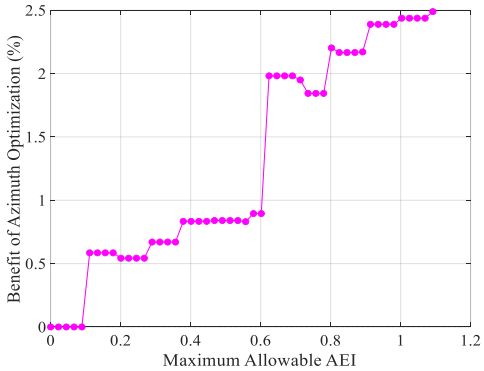


Figure 4. Relative irradiation benefit obtained by including azimuth optimization at equal AEI

Compromise Solutions

The compromise solution represents a more practically relevant operating point than the maximum-irradiation endpoint because it simultaneously accounts for energy capture and orientation effort. The joint tilt-azimuth compromise solution provides an annual POA irradiation of 1825 kWh/m^2 at an AEI of 0.6061, whereas the tilt-only compromise solution provides 1790.9 kWh/m^2 at an AEI of 0.6141. Both configurations require six orientation adjustments. Therefore, joint optimization increases annual irradiation by $\Delta H = 1825 - 1790.9 = 34.1$ kWh/m^2, which corresponds to an improvement of 1.901%.

Moreover, this improvement is achieved with a slightly lower AEI. The difference between the compromise AEI values is -0.008, while the tilt-only strategy retains 98.135% of the irradiation obtained from the joint compromise solution. This result is significant because the benefit of azimuth optimization is obtained without increasing the number of physical interventions. Both systems require six adjustments over the year. Instead, the additional degree of freedom allows the orientation movement to be distributed between tilt and azimuth. The cumulative tilt movement decreases substantially from 68° in the tilt-only system to only 29° in the joint system, while the latter introduces 62° of cumulative azimuth movement. Thus, the optimization does not simply add azimuth movement on top of an unchanged tilt schedule. It produces a fundamentally different orientation trajectory in which tilt and azimuth adjustments complement one another.

Monthly Orientation Characteristics

Fig. 5 compares the monthly tilt angles associated with the two compromise solutions. The tilt-only solution exhibits a pronounced seasonal variation. The panel tilt decreases from 49° in January to 17° during May-August and subsequently increases to 53° in November and December. In contrast, the joint optimization results in a considerably narrower tilt range. The optimized tilt is 41° in January and February, decreases gradually to 27° during May-August, and subsequently increases to approximately 42° during October-December. This explains the substantially smaller cumulative tilt displacement of the joint solution.

The reduction in tilt variation occurs because part of the seasonal orientation correction is transferred to the azimuth axis. As shown in Fig. 6, the compromise azimuth angles vary from approximately -10° during the winter months to approximately -41° during May-July before returning toward -10° toward the end of the year.

This behavior demonstrates an important characteristic of multi-axis orientation optimization: the tilt and azimuth angles should not necessarily be optimized independently. Rather, they form a coupled orientation decision. Allowing azimuth variation changes the optimal tilt trajectory itself, which explains why the joint solution requires only 29° of cumulative tilt displacement compared with 68° for the tilt-only configuration.

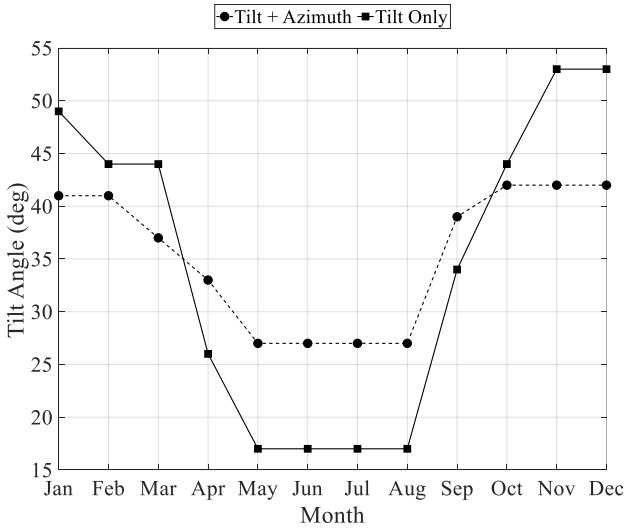


Figure 5. Monthly tilt angles corresponding to the compromise solutions of the two optimization strategies.

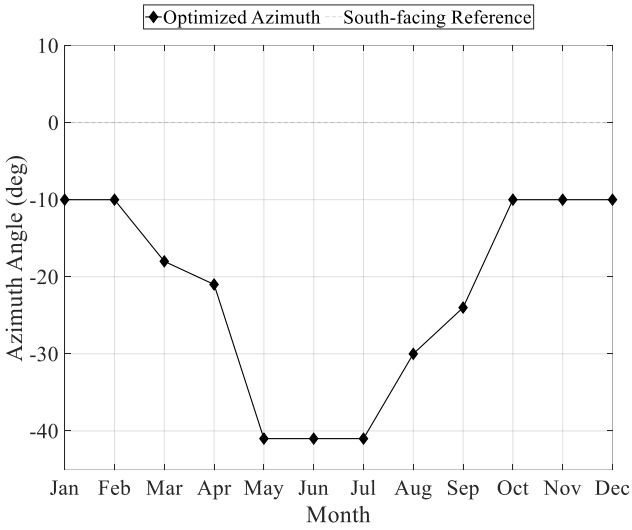


Figure 6. Monthly azimuth angles corresponding to the compromise solution of the joint tilt-azimuth optimization.

Conclusion

This study developed a multi-objective optimization framework for determining monthly PV orientations by simultaneously maximizing annual POA irradiation and minimizing the effort associated with orientation adjustments. The proposed AEI provides a common measure of adjustment requirements by considering both the number of orientation interventions and the cumulative angular movements. Two orientation strategies were investigated: joint optimization of monthly tilt and azimuth angles and tilt-only optimization with a fixed south-facing azimuth.

The results demonstrated a clear trade-off between solar irradiation capture and orientation adjustment effort. Joint tilt-azimuth optimization achieved a maximum annual POA irradiation of 1841.8 kWh/m², compared with 1796.9 kWh/m² for tilt-only optimization, corresponding to an improvement of approximately 2.50%. For the selected compromise solutions, the annual POA irradiation increased from 1790.9 kWh/m² for the tilt-only strategy to 1825.0 kWh/m² for the joint strategy, representing an improvement of approximately 1.90%. Both compromise solutions required only six orientation interventions over the year. Furthermore, the joint strategy reduced the cumulative tilt movement from 68° to 29° by distributing the required orientation changes between the tilt and azimuth degrees of freedom.

The equal-AEI analysis further showed that the additional azimuth degree of freedom can provide higher attainable POA irradiation without requiring a greater overall adjustment effort. Therefore, the benefit of azimuth optimization should not be assessed solely from the maximum achievable irradiation, but rather by considering its interaction with the practical effort required for periodic reorientation. Overall, the proposed framework provides a systematic approach for balancing solar irradiation capture and adjustment requirements and can support the design and operation of periodically adjustable PV systems. Future studies may extend the framework by incorporating PV power-generation characteristics, economic costs associated with orientation adjustments, different climatic conditions, and experimentally implemented adjustment mechanisms.

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NUMERICAL INVESTIGATION OF FOCAL-LENGTH SCALING IN GAP METALENSES AT 850 NM

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ABSTRACT
Metalenses are flat lenses composed of subwavelength meta-atoms that manipulate the incident wavefront to focus light at a desired point. In metalens design, the choice of material for the meta-atoms plays a key role in the focusing performance and manufacturability of a metalens. Accordingly, over the past decade, numerous plasmonic, alternative plasmonic, and all-dielectric based metalens designs have been developed in the visible and near-infrared (NIR) spectral ranges, and their focusing performances have been systematically demonstrated. Gallium phosphide (GaP) is also a high-refractive-index dielectric material and offers strong light confinement capabilities. In the visible and NIR region, GaP exhibits a high refractive index combined with low optical absorption. These properties make it a promising alternative to commonly used high-index dielectric materials for metasurface-based applications. Despite these advantages, GaP-based metalens designs remain limited in the literature, especially in the NIR regime. This gap indicates an opportunity to explore GaP as a practical and high-performance platform for metalens implementations. In this work, the focal-length-dependent performance of fixed-aperture GaP metalenses is systematically investigated at 850 nm using full-wave electromagnetic simulations. Three metalenses with an identical diameter of 200 μm and focal lengths of 1000, 500, and 200 μm were designed, corresponding to numerical apertures (NA) of 0.10, 0.196, and 0.45, respectively. The simulated average focal spot full-width half-maximums (FWHM) were 4.30, 2.23, and 1.00 μm, with corresponding depths of focus (DOF) of 145.5, 38.1, and 7.1 μm. The absolute focusing efficiencies were also calculated as 71%, 67%, and 50%, respectively, revealing reduced efficiency as stronger confinement was achieved at higher NA. Overall, the results establish a quantitative resolution–DOF–efficiency trade-off for GaP metalenses at 850 nm and characterize GaP as a promising dielectric platform for NIR flat-optical systems.
Keywords: metalens, focusing efficiency, gallium-phosphide

A MEASUREMENT AND INSPECTION SYSTEM FOR REMOTE DETECTION OF HEADLAMP ALIGNMENT AND LIGHTING CHARACTERISTICS OF MOVING VEHICLES

SEYIR HALİNDEKI TAŞITLARIN FAR AYARI VE IŞIK ÖZELLİKLERİNİN UZAKTAN TESPİTİNE YÖNELİK BİR ÖLÇÜM VE DENETİM SİSTEMİ

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Abstract
Proper headlamp alignment and adequate lighting performance are essential for safe night-time driving. Incorrectly aimed or excessively bright headlamps can impair the visibility of other road users and increase glare-related safety risks. Conventional headlamp inspection is generally carried out during periodic vehicle inspections using dedicated aiming equipment while the vehicle is stationary. Consequently, changes or faults occurring after inspection cannot be effectively monitored under normal traffic conditions. This paper presents a remote measurement and inspection system designed to evaluate the headlamp alignment and lighting characteristics of moving vehicles without interrupting traffic flow. The system combines photometric imaging, optical sensing, image processing, and automatic number plate recognition capabilities. Measurement units can be deployed beside or above the roadway, as well as on mobile platforms, allowing the system to operate under real-world driving conditions. Headlamp emissions are captured and processed to determine parameters including vertical alignment, optical axis angle, luminous intensity, spatial light distribution, and color temperature. The measured parameters are evaluated against predefined reference limits based on vehicle type and applicable national and international lighting standards. This enables the automatic identification of conditions such as incorrect headlamp alignment, insufficient or excessive light output, abnormal light distribution, and inactive headlamps. When a non-compliant lighting condition is identified, the vehicle number plate is automatically detected and associated with the corresponding measurement data. The system can also transmit measurement and violation records to central inspection and monitoring systems through wired or wireless communication technologies. The developed system provides a practical framework for non-contact and remote monitoring of vehicle lighting performance under real-world traffic conditions and offers a potential solution for improving traffic safety and reducing headlamp-related glare.
Keywords: Vehicle headlamp, Headlamp alignment, Photometric measurement, Luminous intensity, Light distribution, Image processing, Automatic number plate recognition, Traffic safety.

Özet
Farların uygun şekilde hizalanması ve yeterli aydınlatma performansına sahip olması, gece sürüş güvenliği açısından büyük önem taşımaktadır. Yanlış hizalanmış veya aşırı parlak farlar, diğer yol kullanıcılarının görüşünü olumsuz etkileyebilmekte ve göz kamaşmasına bağlı güvenlik risklerini artırabilmektedir. Geleneksel far denetimleri genellikle periyodik araç muayeneleri sırasında, taşıt sabit durumdayken özel far ayar cihazları kullanılarak gerçekleştirilmektedir. Bu nedenle, muayene sonrasında meydana gelen değişikliklerin veya arızaların normal trafik koşullarında etkin bir şekilde izlenmesi mümkün olmamaktadır. Bu çalışmada, seyir hâlindeki taşıtların far hizalamasını ve aydınlatma özelliklerini trafik akışını kesintiye uğratmadan değerlendirmek üzere geliştirilen uzaktan bir ölçüm ve denetim sistemi sunulmaktadır. Sistem; fotometrik görüntüleme, optik algılama, görüntü işleme ve otomatik plaka tanıma yeteneklerini bir araya getirmektedir. Ölçüm birimleri yol kenarına, yol üstüne veya mobil platformlar üzerine yerleştirilebilmekte ve böylece sistemin gerçek sürüş koşullarında çalışmasına olanak sağlanmaktadır. Far ışığı yakalanarak işlenmekte ve düşey hizalama, optik eksen açısı, ışık şiddeti, uzamsal ışık dağılımı ve renk sıcaklığı gibi parametreler belirlenmektedir. Elde edilen ölçüm parametreleri, taşıt türüne bağlı olarak tanımlanan referans sınır değerler ve geçerli ulusal ve uluslararası aydınlatma standartları ile karşılaştırılmaktadır. Böylece far hizasının uygun olmaması, yetersiz veya aşırı ışık çıkışı, anormal ışık dağılımı ve çalışmayan farlar gibi durumların otomatik olarak belirlenmesi sağlanmaktadır. Mevzuata uygun olmayan bir aydınlatma durumu tespit

edildiğinde, taşıtın plaka bilgisi otomatik olarak belirlenerek ilgili ölçüm verileriyle ilişkilendirilmektedir. Sistem ayrıca ölçüm ve ihlal kayıtlarını kablolu veya kablosuz haberleşme teknolojileri üzerinden merkezi denetim ve izleme sistemlerine aktarabilmektedir. Geliştirilen sistem, gerçek trafik koşullarında taşıtların aydınlatma performansının temassız ve uzaktan izlenmesi için uygulanabilir bir altyapı sağlamakta ve trafik güvenliğinin artırılması ile far kaynaklı göz kamaşmasının azaltılmasına yönelik potansiyel bir çözüm sunmaktadır.

Anahtar kelimeler: Taşıt farı, Far ayarı, Fotometrik ölçüm, Işık şiddeti, Işık dağılımı, Görüntü işleme, Otomatik plaka tanıma, Trafik güvenliği

DESIGN, MANUFACTURING, AND TESTING OF A CORRUGATED-WALL TRANSFORMER WITH A CONVENTIONAL OIL-TYPE ON-LOAD TAP CHANGER

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ABSTRACT
This study focuses on developing a compact, economical, and manufacturable transformer design with a conventional oil-type On-Load Tap Changer (OLTC), as an alternative to the conventional radiator-cooled power transformer configuration. Oil-immersed transformers consist of integrated components, including windings, core, insulation materials, insulating oil, mechanical parts, and accessories. In transformers equipped with OLTCs, the cooling arrangement and installation volume can significantly affect overall dimensions, weight, oil volume, and cost. Increasing market competition and demand for compact, cost-effective transformer solutions have therefore increased the importance of optimizing existing designs.
Conventional oil-type transformers equipped with OLTCs are generally designed with radiator-based cooling systems. The use of radiators may result in increased external dimensions, higher oil volume and overall weight, as well as additional manufacturing, transportation, and installation costs. Within the scope of this project, a corrugated-wall tank design is developed as an alternative to this configuration. By incorporating the cooling surface directly into the transformer tank, the proposed design aims to eliminate external radiators and achieve a more compact transformer configuration.
The developed transformer design considers the electrical, thermal, and mechanical requirements of the system while providing reliable integration of the OLTC. The manufacturability of the proposed configuration and its performance under operating conditions are verified through manufacturing and testing activities.
As a result, the project presents an alternative design approach for reducing the dimensions, weight, and oil volume of conventional oil-type transformers equipped with OLTCs. The developed corrugated-wall transformer has significant potential to reduce manufacturing and material costs while providing advantages in lead time, transportation, and installation compared with conventional radiator-cooled designs. The proposed solution offers a technically feasible approach for developing more compact and cost-effective OLTC-equipped transformers.
Keywords: Oil-Type Transformer; On-Load Tap Changer (OLTC); Corrugated-Wall Transformer

IDENTIFICATION OF POTENTIAL PTP1B INHIBITORS IN TYPE 2 DIABETES BY PHARMACOPHORE-BASED VIRTUAL SCREENING

TİP 2 DİYABETTE POTANSİYEL PTP1B İNHİBİTÖRLERİNİN FARMAKOFOR-TEMELLİ SANAL TARAMA İLE BELİRLENMESİ

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ÖZET

Protein tirozin fosfataz 1B (PTP1B), insülin reseptörü ile insülin reseptör substratlarını defosforile ederek insülin sinyalini baskılayan ve leptin yolağındaki JAK2'yi hedef alarak enerji dengesini düzenleyen bir negatif düzenleyicidir. Bu çifte rolü nedeniyle tip 2 diyabet ve obezite tedavisinde doğrulanmış bir terapötik hedef olarak kabul edilmektedir. Ancak enzimin derin, dar ve pozitif yüklü katalitik cebinin PTP ailesi genelinde yüksek oranda korunmuş olması seçici inhibitör tasarımını güçleştirmekte; fosfotirozin taklidi ilk nesil bileşiklerin anyonik yapısı ise zayıf hücre geçirgenliği ve düşük oral biyoyararlanıma yol açmaktadır. Nitekim Faz II'ye ulaşabilen tek aday olan Ertiprotafib'in geliştirilmesi durdurulmuş olup, günümüzde klinik kullanıma onaylanmış bir PTP1B inhibitörü bulunmamaktadır. Bu çalışmada, PTP1B'nin katalitik bölgesini hedefleyen yeni inhibitör adaylarının farmakofor temelli sanal tarama yaklaşımıyla belirlenmesi amaçlanmıştır. Çalışmada hedef yapı olarak, katalitik cebine 6-(oksalilamino)-1H-indol-5-karboksilik asit (OAI) inhibitörü bağlı hâlde bulunan 1C83 kodlu PTP1B kristal yapısı kullanılmıştır. Yapı UCSF Chimera Dock Prep modülü ile kenetlenmeye hazırlanmış, OAI'nin bağlanma profili ayrıntılı biçimde incelenerek grid box parametreleri tanımlanmış ve oluşturulan protokol, OAI'nin aynı bölgeye yeniden kenetlenmesi (re-docking) yoluyla doğrulanmıştır. OAI'nin PTP1B ile kurduğu etkileşimler Pharmit platformunda analiz edilerek altı noktalı bir farmakofor sorgusu oluşturulmuş; bu sorgu ile ZINC Purchasable veritabanı taranarak 31.146 bileşikten oluşan bir ilaç kütüphanesi hazırlanmıştır. Kütüphane, PyRx arayüzünde çalıştırılan AutoDock Vina algoritması ile aynı bağlanma bölgesine kenetlenmiş, OAI, Ertiprotafib ve JTT-551 referans bileşikler olarak kullanılmıştır. Öne çıkan adayların ADME profilleri SwissADME, toksisite profilleri ise ProTox 3.0 çevrim içi sunucusunda öngörülmüştür. Yeniden kenetlenen OAI'nin kristal yapıdaki deneysel konformasyon ile 2 Å'ın altında RMSD sergilemesi ve kristal yapıdaki etkileşim ağını eksiksiz biçimde yeniden üretmesi, kurgulanan protokolü doğrulamıştır. Sanal tarama sonucunda -7 kcal/mol eşiğinin altında bağlanma enerjisi sergileyen ve katalitik cebin kritik rezidüleriyle anlamlı temas kuran 24 bileşik belirlenmiş; bunlar arasından ZINC000106540127 (-8,2 kcal/mol), ZINC000004879765 (-8,0 kcal/mol) ve ZINC000006760732 (-8,0 kcal/mol) en umut vaat edici adaylar olarak seçilmiştir. Üç bileşiğin de, birbirinden belirgin biçimde farklı kimyasal iskeletlere sahip olmalarına rağmen Tyr46, Asp181, Ala217 ve Arg221 rezidüleriyle ortak biçimde etkileşim kurduğu belirlenmiştir. ADME değerlendirmesinde adayların tamamı düşük molekül ağırlığı (246–299 g/mol), düşük lipofilisite (Log *P*o/w 0,71–1,01), yüksek gastrointestinal emilim ve "çözünür" sınıfında yer alan çözünürlük değerleri sergilemiş; hiçbirinin kan–beyin bariyerini geçmediği ve P-glikoprotein substratı olmadığı öngörülmüştür. Bu profil, aşırı lipofilik ve pratik olarak çözünmez yapıdaki Ertiprotafib ve JTT-551 ile belirgin bir karşıtlık oluşturmuştur. Toksisite analizinde ZINC000006760732, 1500 mg/kg LD50 değeri ile mutajenite ve karsinojenite açısından temiz profili sayesinde en elverişli güvenlik profilini sergilemiştir. Elde edilen bulgular, farmakofor temelli sanal taramanın PTP1B'nin katalitik cebine yönelik yeni kimyasal iskeletlerin belirlenmesinde etkili bir strateji olduğunu ortaya koymaktadır. Öne çıkan üç bileşik, bilinen inhibitörlere kıyasla üstün ilaç benzerliği ve farmakokinetik profil sergilemekte olup, moleküler dinamik simülasyonları ve deneysel doğrulama çalışmaları ile detaylandırılmaya aday niteliktedir.

Anahtar Kelimeler: PTP1B, tip 2 diyabet, farmakofor temelli sanal tarama, moleküler kenetlenme, in siliko ADME/toksisite öngörüsü

ABSTRACT

Protein tyrosine phosphatase 1B (PTP1B) is a negative regulator of insulin signalling that dephosphorylates the insulin receptor and insulin receptor substrates, and that also governs energy balance by targeting JAK2 downstream of the leptin receptor. This dual role has established the enzyme as a validated therapeutic target for type 2 diabetes and obesity. However, the deep, narrow and positively charged catalytic pocket of PTP1B is highly conserved across the PTP family, which complicates the design of selective inhibitors, while the anionic nature of first-generation phosphotyrosine-mimetic compounds results in poor cell permeability and low oral bioavailability. Indeed, Ertiprotafib, the only candidate to have reached Phase II, was discontinued, and no PTP1B inhibitor is currently approved for clinical use. The present study aimed to identify novel inhibitor candidates targeting the catalytic site of PTP1B through a pharmacophore-based virtual screening approach. The PTP1B crystal structure deposited under the code 1C83, which contains 6-(oxalylamino)-1H-indole-5-carboxylic acid (OAI) bound within its catalytic pocket, was selected as the target structure. The structure was prepared for docking using the Dock Prep module of UCSF Chimera, and the grid box parameters were defined by examining the binding profile of OAI in detail. The resulting protocol was validated by re-docking OAI into the same site. The interactions established between OAI and PTP1B were subsequently analysed in the Pharmit platform to construct a six-point pharmacophore query, and screening of the ZINC Purchasable database with this query yielded a compound library comprising 31,146 molecules. The library was docked into the same binding site using the AutoDock Vina algorithm implemented in PyRx, with OAI, Ertiprotafib and JTT-551 serving as reference compounds. ADME profiles of the prioritised candidates were predicted using the SwissADME server, and their toxicity profiles using the ProTox 3.0 server. The re-docked OAI pose deviated from the experimental conformation by less than 2 Å RMSD and fully reproduced the crystallographic interaction network, thereby validating the docking protocol. Virtual screening identified 24 compounds that exhibited binding energies below the -7 kcal/mol threshold while establishing meaningful contacts with the critical residues of the catalytic pocket. Among these, ZINC000106540127 (-8.2 kcal/mol), ZINC000004879765 (-8.0 kcal/mol) and ZINC000006760732 (-8.0 kcal/mol) were selected as the most promising candidates. Despite possessing markedly different chemical scaffolds, all three compounds engaged Tyr46, Asp181, Ala217 and Arg221 in common. ADME predictions indicated that all candidates combined low molecular weight (246–299 g/mol), low lipophilicity (Log Po/w 0.71–1.01), high gastrointestinal absorption and solubility values falling within the "soluble" class, while none was predicted to cross the blood–brain barrier or to act as a P-glycoprotein substrate. This profile contrasted sharply with the highly lipophilic and practically insoluble reference inhibitors Ertiprotafib and JTT-551. In the toxicity analysis, ZINC000006760732 displayed the most favourable safety profile, with an LD50 of 1500 mg/kg together with negative predictions for both mutagenicity and carcinogenicity. These findings demonstrate that pharmacophore-based virtual screening is an effective strategy for identifying novel chemical scaffolds directed against the catalytic pocket of PTP1B. The three prioritised compounds display superior drug-likeness and pharmacokinetic profiles compared with the known inhibitors, and represent suitable candidates for further characterisation through molecular dynamics simulations and experimental validation.

Keywords: PTP1B, type 2 diabetes, pharmacophore-based virtual screening, molecular docking, in silico ADME/toxicity prediction

1. GİRİŞ

PTPN1 geni tarafından kodlanan protein tirozin fosfataz 1B (PTP1B), PTP süper ailesinin ~50 kDa ağırlığındaki, transmembran olmayan ve ilk karakterize edilen üyelerinden biridir (Liu ve ark., 2022). Endoplazmik retikulumun sitoplazmik yüzeyine bağlı konumlanan enzim, insülin sinyalinin başlıca negatif düzenleyicisi olarak işlev görmektedir. Aktive olmuş insülin reseptörü ile IRS-1/IRS-2'yi defosforile ederek PI3K/Akt aracılı glukoz alımını azaltmaktadır (Abdelsalam, Korashy, Zeidan ve Agouni, 2019; Sun, Dinenno, Tang ve Kontaridis, 2024). Leptin reseptörü altındaki JAK2'yi defosforile ederek hipotalamik STAT3 aktivasyonunu sınırlandırmakta, böylece tokluk hissi ve enerji harcamasını da etkilemektedir (Kołodziej-Sobczak, Sobczak ve Łączkowski, 2024). Bu çifte rol, PTP1B eksikliği olan farelerde gözlenen artmış insülin duyarlılığı, iyileşmiş glukoz toleransı ve diyetle indüklenen obeziteye direnç ile doğrulanmıştır (Elchebly ve ark., 1999; Klaman ve ark., 2000).

Bu düzenleyici konumu nedeniyle PTP1B disregülasyonu geniş bir hastalık yelpazesiyle ilişkilendirilmektedir. Karaciğer, kas ve hipotalamik nöronlardaki artmış aktivitesi tip 2 diyabet ve obezitede birleşik insülin-leptin direncine katkı sağlarken (Bence ve ark., 2006; Kołodziej-Sobczak ve ark., 2024), PI3K/eNOS aracılı nitrik oksit yolağını baskılayarak endotel disfonksiyonu ve kardiyovasküler hastalığa yol açmaktadır (Abdelsalam ve ark., 2019; Sun ve ark., 2024). Onkolojide daha bağlam-bağımlı bir rol üstlenmekte; HER2-pozitif meme kanserinde tümör başlangıcını tetikleyebilirken farklı dokularda tümör baskılayıcı gibi de davranabilmektedir (Kołodziej-Sobczak ve ark., 2024; Krishnan ve ark., 2014). Ayrıca Alzheimer, Parkinson ve majör depresif bozuklukla ilişkilendirilerek terapötik önemi metabolik hastalığın ötesine taşınmaktadır (Kołodziej-Sobczak ve ark., 2024).

Yapısal olarak 435 amino asitlik PTP1B; bir N-terminal katalitik domain (~1–300), bir düzenleyici segment (~300–400) ve enzimi ER membranına bağlayan hidrofobik bir C-terminal kuyruktan (~400–435) oluşmaktadır (Liu ve ark., 2022). Katalitik domain, aktif bölgeyi oluşturan esnek halkaların yer aldığı kompakt bir α/β katlanması sergilemektedir. Kataliz değişmez nükleofilik Cys215 kalıntısına dayanırken, WPD halkasının bağlanmış substrat üzerine kapanması reaksiyon döngüsünü tamamlamaktadır (Woods, Abzalimov ve Keedy, 2024). Derin, dar ve pozitif yüklü aktif bölge PTP ailesi genelinde yüksek oranda korunmuş olup seçici inhibitör tasarımını güçleştirmektedir. Bu kısıtlama, katalitik merkezden ~20 Å uzaklıktaki α7 heliks bölgesi ve içsel olarak düzensiz C-terminal segment gibi allosterik bağlanma yüzeylerinin araştırılmasını tetiklemiştir (Krishnan ve ark., 2014; Woods ve ark., 2024).

PTP1B-knockout modellerinden elde edilen genetik doğrulama ve farmakolojik inhibisyonun hepatik lipid birikimi olmaksızın glukoz homeostazını iyileştirdiğine dair bulgular, bu enzime yönelik iki on yılı aşkın süredir devam eden ilaç keşfi çabalarını desteklemektedir (Abdelsalam ve ark., 2019; Elchebly ve ark., 1999). Ancak aktif bölgeye yönelik ilk nesil fosfotirozin-mimetik inhibitörlerin polar, anyonik yapısı zayıf hücre geçirgenliği ve oral biyoyararlanıma yol açarak klinik ilerlemeyi sınırlandırmıştır (Liu ve ark., 2022). Faz II'ye ulaşan tek bileşik olan Ertiprotafib, hedef-dışı etkiler ve yetersiz etkinlik nedeniyle geliştirilmesi durdurulmuştur (Erbe ve ark., 2005; Liu ve ark., 2022). İlgi daha sonra aktif bölge dışındaki yüzeyleri de hedefleyen ligandlara kaymış; tiyazol bazlı ve karışık tip (mixed-type) inhibisyon sergileyen JTT-551, 0,22 μM'lik Ki değeri ve TCPTP'ye kıyasla 40 kattan fazla seçicilikle, diyetle indüklenen obez ve diyabetik fare modellerinde insülin- ve leptin-bağımlı parametreleri iyileştirmiştir (Fukuda ve ark., 2010; Ito, Fukuda, Sakata, Morinaga ve Ohta, 2014). Buna rağmen henüz onaylanmış bir PTP1B inhibitörü bulunmamakta, bu da katalitik ve allosterik bölgeleri hedefleyen yapı temelli ve hesaplamalı ilaç keşfi stratejilerini motive etmeye devam etmektedir.

Bu çalışmada, PTP1B kristal yapısını hedefleyen yeni inhibitör adaylarının farmakofor temelli sanal tarama stratejisiyle keşfedilmesi amaçlanmaktadır. PDB'den indirilen kristal yapı içerisindeki inhibitörün (OAI) etkileşimleri incelenerek farmakofor özellikleri belirlenmiş ve aynı özelliklere sahip bileşiklerden oluşan bir ilaç kütüphanesi hazırlanmıştır. OAI, Ertiprotafib ve JTT-551'in kontrol grubu olarak kullanıldığı farmakofor temelli sanal tarama ile bilinen inhibitörlere alternatif olabilecek yeni bileşikler belirlenmiştir. Bilinen ve yeni keşfedilen bileşiklerin ADME ve toksisite profilleri in siliko yöntemlerle karşılaştırmalı olarak değerlendirilmiştir. Elde edilen bulgular, ileride gerçekleştirilecek moleküler dinamik simülasyonlarıyla detaylandırılarak literatüre PTP1B inhibisyonuna yönelik yeni aday bileşikler kazandırılacaktır.

2. MATERYAL VE YÖNTEM

2.1.Protein Yapısının Hazırlanması ve Grid Box Dizaynı

Çalışmanın hedef proteini olan insan protein tirozin fosfataz 1B (PTP1B) enziminin üç boyutlu kristal yapısı, RCSB Protein Veri Bankası'ndan (PDB) temin edilmiştir (Berman ve ark., 2000). Hedef yapı olarak, enzimin katalitik bölgesine bağlanmış hâlde 6-(oksalilamino)-1H-indol-5-karboksilik asit (OAI) inhibitörünü içeren 1C83 kodlu yapı seçilmiş ve .pdb formatında indirilmiştir (Andersen ve ark., 2000). Bu yapının tercih edilmesinin başlıca nedenleri, çözünürlüğünün moleküler yerleştirme çalışmaları için yeterli düzeyde olması, katalitik cebin ligand bağlı (holo) konformasyonda çözülmüş olması ve kompleks hâlindeki OAI'nin fosfat taklidi niteliği taşıyarak bağlanma bölgesinin farmakofor gereksinimleri hakkında doğrudan yapısal bilgi sunmasıdır. İndirilen yapı, moleküler yerleştirme analizlerine hazırlanmak üzere UCSF Chimera yazılımının (sürüm 1.16) Dock Prep modülüne aktarılmıştır (Pettersen ve ark., 2004). Hazırlama aşamasında, kristalografik su molekülleri ve yapıda

bulunan diğer heteroatom gruplar yapıdan uzaklaştırılmış, eksik yan zincirler Dunbrack rotamer kütüphanesi kullanılarak tamamlanmış (Shapovalov ve Dunbrack, 2011), yapıya fizyolojik pH koşulları dikkate alınarak polar hidrojen atomları eklenmiş ve kısmi atomik yükler AMBER ff14SB kuvvet alanı parametreleri temel alınarak atanmıştır (Maier ve ark., 2015; Wang, Wang, Kollman ve Case, 2006). Hazırlanan reseptör yapısı, sonraki analizlerde kullanılmak üzere .pdbqt formatında kaydedilmiştir. Moleküler yerleştirme analizlerinin gerçekleştirileceği arama uzayı (grid box), kristal yapıda OAI'nin bağlanma profili ayrıntılı biçimde incelenerek ve ligandın temas kurduğu katalitik cep rezidüleri referans alınarak tanımlanmıştır. Bu doğrultuda grid box'ın merkez koordinatları x = 44,38, y = 13,77 ve z = 2,55 olarak belirlenmiş; kutu boyutları ise x, y ve z eksenlerinin her biri için 10 Å olacak şekilde 10 × 10 × 10 Å olarak ayarlanmıştır. Belirlenen bu arama uzayının, PTP1B'nin fosfat bağlayıcı P-ilmiğini (Ser216–Arg221), WPD-ilmiği üzerindeki katalitik Asp181 rezidüsünü ve cebin hidrofobik duvarını oluşturan Tyr46 rezidüsünü eksiksiz biçimde kapsadığı doğrulanmıştır.

2.2.Bilinen İnhibitörlerin Moleküler Kenetlenmesi

Moleküler yerleştirme protokolünün doğrulanması amacıyla kullanılan referans bileşiklerden Ertiprotafib ve JTT-551'in üç boyutlu yapıları ZINC15 (Sterling ve Irwin, 2015) ve PubChem (Kim ve ark., 2023) veritabanlarından, kristal yapıda PTP1B'ye bağlı hâlde bulunan OAI inhibitörünün yapısı ise RCSB Protein Veri Bankası'ndan (Berman ve ark., 2000) .sdf formatında indirilmiştir. İndirilen üç ligand, moleküler yerleştirme analizleri için PyRx sanal tarama platformuna (sürüm 0.8) aktarılmıştır (Dallakyan ve Olson, 2015). Yerleştirme işleminden önce, bileşiklerin enerjetik açıdan uygun konformasyonlar benimsemesini sağlamak amacıyla her bir ligand PyRx bünyesindeki Open Babel modülü kullanılarak enerji minimizasyonuna tabi tutulmuştur (O'Boyle ve ark., 2011). Minimizasyon işleminde Evrensel Kuvvet Alanı (Universal Force Field, UFF) ve eşlenik gradyan (conjugate gradient) algoritması tercih edilmiştir (Rappé, Casewit, Colwell, Goddard ve Skiff, 1992). Minimize edilen yapılar, döngüsel olmayan bağların dönebilir (rotatable) kabul edildiği koşullarda AutoDock ligandı formatına (.pdbqt) dönüştürülmüştür. Hazırlanan üç ligand, bir önceki aşamada tanımlanan grid box parametreleri (merkez: 44,38; 13,77; 2,55 — boyut: 10 × 10 × 10 Å) kullanılarak, PyRx arayüzünde çalıştırılan AutoDock Vina algoritması ile PTP1B'nin katalitik bölgesine dock edilmiştir (Trott ve Olson, 2010). Yerleştirme çalışmaları, yazılımın varsayılan kapsamlılık (exhaustiveness) değeri olan 8 ile gerçekleştirilmiş ve her bir ligand için dokuz adet bağlanma pozu üretilmiştir. Üretilen pozlar arasından en düşük bağlanma enerjisine sahip olan konformasyon, ilgili bileşiğin en olası bağlanma modu olarak kabul edilmiş ve sonraki analizlerde değerlendirilmiştir. OAI için elde edilen en iyi poz, aynı ligandın 1C83 kodlu kristal yapıdaki deneysel konformasyonu ile üst üste bindirilmiş ve iki poz arasındaki karesel ortalama sapma (RMSD) değeri hesaplanarak, tanımlanan grid box parametrelerinin ve yerleştirme protokolünün deneysel bağlanma modunu yeniden üretebilme başarısı sınanmıştır.

2.3.Farmakofor Modelinin Oluşturulması ve Farmakofor Temelli Bileşik Kütüphanesinin Hazırlanması

Doğrulanan bağlanma bölgesinin kimyasal ve geometrik gereksinimlerini sistematik biçimde tanımlamak amacıyla, yapı temelli farmakofor modelleme ve sanal tarama işlemleri Pharmit çevrim içi platformu kullanılarak gerçekleştirilmiştir (Sunseri ve Koes, 2016). Bu amaçla, PTP1B'nin katalitik cebine bağlı hâlde OAI inhibitörünü içeren 1C83 kodlu kompleks yapı, reseptör ve ligand bileşenleri ayrı ayrı olacak şekilde platforma yüklenmiştir. Pharmit, yüklenen kompleks üzerinden ligandın sahip olduğu farmakofor tanımlayıcılarını (hidrojen bağı alıcısı ve vericisi, hidrofobik bölge, aromatik halka, pozitif ve negatif iyonlaşabilir gruplar) otomatik olarak çıkarmış ve bunların üç boyutlu uzaydaki konumlarını hesaplamıştır. Otomatik olarak üretilen tanımlayıcılar arasından, OAI'nin PTP1B ile kurduğu etkileşimlerin analizine dayanılarak sorguda yer alacak özellikler seçilmiştir. Buna göre, ligandın karboksilat ve oksalilamino gruplarına karşılık gelen beş adet hidrojen bağı alıcısı ile indol çekirdeğini temsil eden bir adet hidrofobik özellik etkin hâle getirilmiş; birbiriyle örtüşen iki hidrojen bağı alıcısı ile iki negatif iyon tanımlayıcısı ise sorgu dışı bırakılmıştır. Negatif iyon tanımlayıcılarının kapatılması, taramanın yalnızca yüklü fosfat taklidi yapılarla sınırlanmasını engellemek ve kimyasal çeşitliliği daha yüksek bir aday havuzuna ulaşmak amacıyla tercih edilmiştir. Etkin hâle getirilen altı farmakofor özelliğinin her biri için tolerans yarıçapı, platformun varsayılan değeri olan 1,0 Å olarak korunmuştur. Oluşturulan bu altı noktalı farmakofor sorgusu ile ZINC Purchasable veritabanı (Sterling ve Irwin, 2015) taranmış ve tanımlanan geometrik düzeni karşılayan bileşikler, farmakofor uyum RMSD değerlerine göre artan sırada listelenmiştir. Tarama sonucunda elde edilen toplam 31.146 bileşik, sonraki

aşamada gerçekleştirilecek moleküler yerleştirme temelli sanal tarama çalışmasının bileşik kütüphanesini oluşturmak üzere .sdf formatında indirilmiştir.

2.4.Sanal İlaç Taraması

Farmakofor sorgusu aracılığıyla oluşturulan 31.146 bileşiklik kütüphane, PTP1B'nin katalitik bölgesine yönelik moleküler kenetlenme temelli sanal ilaç taramasına tabi tutulmuştur. Bu amaçla .sdf formatında indirilen bileşik kütüphanesinin tamamı, referans inhibitörler için uygulanan protokolle birebir aynı olacak şekilde PyRx sanal tarama platformuna (sürüm 0.8) aktarılmıştır (Dallakyan ve Olson, 2015). Kütüphanedeki her bir bileşik, kenetlenme işleminden önce platformun Open Babel tabanlı minimizasyon modülü kullanılarak enerji minimizasyonuna tabi tutulmuş (O'Boyle ve ark., 2011); minimizasyon işleminde Evrensel Kuvvet Alanı (UFF) ve eşlenik gradyan algoritması tercih edilmiştir (Rappé ve ark., 1992). Minimize edilen yapılar, döngüsel olmayan bağların dönebilir kabul edildiği koşullarda toplu biçimde AutoDock ligandı formatına (.pdbqt) dönüştürülmüştür. Hazırlanan kütüphane, protein hazırlama aşamasında OAI'nin bağlanma profili üzerinden tanımlanan ve yeniden yerleştirme analiziyle doğrulanan grid box parametreleri (merkez: 44,38; 13,77; 2,55 — boyut: 10 × 10 × 10 Å) değiştirilmeksizin kullanılarak, PyRx arayüzü üzerinden çalıştırılan AutoDock Vina algoritması ile hazırlanmış PTP1B reseptörüne dock edilmiştir (Trott ve Olson, 2010). Tarama, yazılımın varsayılan kapsamlılık (exhaustiveness) değeri olan 8 ile gerçekleştirilmiş ve her bir bileşik için en düşük bağlanma enerjisine sahip poz, ilgili molekülün en olası bağlanma modu olarak kaydedilmiştir. Tarama tamamlandıktan sonra bileşikler bağlanma enerjilerine göre artan sırada listelenmiş; elde edilen skorlar, aynı grid box kullanılarak kenetlenen referans inhibitörlerin (OAI, Ertiprotafib ve JTT-551) bağlanma enerjileri ile karşılaştırmalı olarak değerlendirilmiştir. Bu değerlendirme sonucunda -7 kcal/mol eşiğinin altında bağlanma enerjisi sergileyen bileşikler öne çıkarılmış ve bu adayların protein–ligand etkileşim profilleri, katalitik cebin kritik rezidüleriyle (Tyr46, Lys120, Asp181, Ser216, Ala217, Gly220 ve Arg221) kurdukları temaslar açısından ayrı ayrı incelenmiştir. Hem bağlanma enerjisi hem de etkileşim profili kriterlerini karşılayan 24 bileşik umut vaat edici aday olarak belirlenmiş, bunlar arasından en düşük bağlanma enerjisine sahip ve referans inhibitörlerin etkileşim ağını en kapsamlı biçimde tekrar eden ilk üç bileşik ileri analizler için seçilmiştir.

2.5.ADME ve Toksisite Profillerinin İn Siliko Değerlendirilmesi

Moleküler kenetlenme analizleri sonucunda öne çıkan üç aday bileşik (ZINC000106540127, ZINC000004879765 ve ZINC000006760732) ile çalışmada referans olarak kullanılan üç bilinen PTP1B inhibitörünün (OAI, Ertiprotafib ve JTT-551) ilaç benzeri özellikleri, farmakokinetik davranışları ve güvenlik profilleri in siliko yöntemlerle değerlendirilmiştir. Bu amaçla toplam altı bileşiğin kanonik SMILES gösterimleri ilgili veritabanlarından elde edilmiş ve analizler bu gösterimler üzerinden gerçekleştirilmiştir. Bileşiklerin absorpsiyon, dağılım, metabolizma ve atılım (ADME) profilleri SwissADME çevrim içi sunucusu kullanılarak öngörülmüştür (Daina, Michielin ve Zoete, 2017). Bu kapsamda her bir bileşik için molekül ağırlığı, kimyasal formül ve topolojik polar yüzey alanı (TPSA) gibi fizikokimyasal parametreler; konsensüs Log P*o/w* değeri üzerinden lipofilisite; ESOL modeli temelinde hesaplanan Log S değeri, çözünürlük miktarı ve çözünürlük sınıfı hesaplanmıştır. Farmakokinetik değerlendirmede, gastrointestinal emilim düzeyi ve kan–beyin bariyeri geçirgenliği BOILED-Egg modeli aracılığıyla tahmin edilmiş (Daina ve Zoete, 2016); ayrıca bileşiklerin P-glikoprotein substratı olup olmadıkları ile CYP1A2, CYP2C19, CYP2C9, CYP2D6 ve CYP3A4 izoformlarına yönelik inhibitör potansiyelleri öngörülmüştür. İlaç benzerliği, Lipinski (Lipinski, Lombardo, Dominy ve Feeney, 2001), Ghose, Veber (Veber ve ark., 2002), Egan ve Muegge filtreleri ile biyoyararlanım skoru üzerinden değerlendirilmiş; medisinal kimya parametreleri kapsamında ise PAINS uyarıları, öncü benzerliği (leadlikeness) ve sentetik erişilebilirlik skorları incelenmiştir. Bileşiklerin toksisite profilleri ProTox 3.0 çevrim içi sunucusu kullanılarak öngörülmüştür (Banerjee, Kemmler, Dunkel ve Preissner, 2024). Bu analizde her bir bileşik için öngörülen oral LD50 değeri (mg/kg) ve GHS sınıflandırmasına dayalı toksisite sınıfı hesaplanmış; organ toksisitesi kapsamında hepatotoksisite, nörotoksisite, nefrotoksisite, solunum toksisitesi ve kardiyotoksisite parametreleri değerlendirilmiştir. Ayrıca toksisite son noktaları başlığı altında karsinojenite, immünotoksisite, mutajenite, sitotoksisite, kan–beyin bariyeri geçişi, ekotoksisite, klinik toksisite ve beslenmeye bağlı toksisite öngörüleri elde edilmiştir. Her iki platformdan elde edilen tüm veriler, aday bileşikler ile referans inhibitörlerin karşılaştırmalı olarak değerlendirilebilmesi amacıyla tablolar hâlinde düzenlenmiştir.

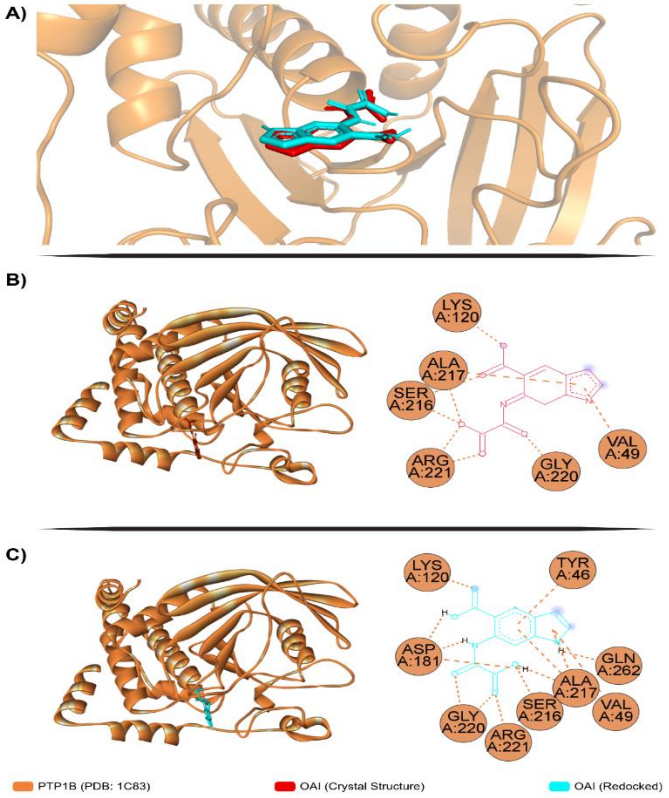
3. BULGULAR VE TARTIŞMA

Moleküler yerleştirme protokolünün ve tanımlanan grid box parametrelerinin güvenilirliğini sınamak amacıyla, 1C83 kodlu kristal yapıda PTP1B'nin katalitik cebine bağlı hâlde bulunan OAI inhibitörü yapıdan uzaklaştırılmış ve aynı kutu koordinatları ile aynı yerleştirme ayarları kullanılarak proteine yeniden yerleştirilmiştir. Elde edilen en düşük bağlanma enerjisine sahip pozun kristal yapıdaki deneysel konformasyon ile üst üste bindirilmesi sonucunda, iki pozun katalitik cep içinde büyük ölçüde örtüştüğü gözlenmiştir (Şekil 1A). Ligandın bisiklik aromatik çekirdeği kristal yapıdaki yönelimini neredeyse birebir korumuş, sınırlı bir sapma yalnızca oksalilamino kolunun torsiyonel yerleşiminde dikkat çekmiştir. İki poz arasında hesaplanan RMSD değeri <2 Å olarak bulunmuştur. Yeniden yerleştirilen pozun bağlanma enerjisi ise -8,2 kcal/mol olarak hesaplanmıştır. Bu bulgular, oluşturulan grid box'ın hedef bağlanma bölgesini doğru biçimde kapsadığını ve seçilen yerleştirme algoritması ile parametrelerinin deneysel bağlanma modunu yeniden üretebilecek doğrulukta olduğunu göstermektedir. Konformasyonel örtüşmenin yanı sıra, kristal yapıdaki ve yeniden yerleştirilen OAI pozlarının protein–ligand etkileşim profilleri de karşılaştırmalı olarak incelenmiştir. Kristal yapıda OAI'nin karboksilat ve oksalilamino gruplarının Lys120, Ser216, Ala217, Gly220 ve Arg221 rezidüleri ile hidrojen bağı temelli bir ağ kurduğu, pirol halkası üzerinden ise Val49 ile ilave bir temas gerçekleştirdiği belirlenmiştir (Şekil 1B). Yeniden yerleştirilen pozda bu altı rezidünün tamamı korunmuş, bunlara ek olarak ligandın Tyr46, Asp181 ve Gln262 rezidüleri ile de etkileşime girdiği gözlenmiştir (Şekil 1C). Korunan temasların Ser216–Ala217–Gly220–Arg221 dizisi üzerinden fosfat bağlayıcı P-ilmiğine karşılık gelmesi, yeniden yerleştirilen pozun PTP1B katalitik cebindeki kanonik tanıma motifini eksiksiz biçimde yeniden ürettiğini ortaya koymaktadır. WPD-ilmiği üzerinde konumlanan Asp181, cebin hidrofobik duvarını oluşturan Tyr46 ve Q-ilmiği rezidüsü Gln262 ile kurulan ilave etkileşimler ise ligandın aktif bölgeye kristal yapıdaki hâline kıyasla daha kapsamlı biçimde gömüldüğüne işaret etmektedir. Hem konformasyonel hem de etkileşim düzeyinde sağlanan bu uyum, kurgulanan yerleştirme stratejisinin PTP1B katalitik bölgesi için geçerli olduğunu doğrulamış ve aynı protokolün bileşik kütüphanesinin sanal taranmasında güvenle kullanılabileceğini göstermiştir.

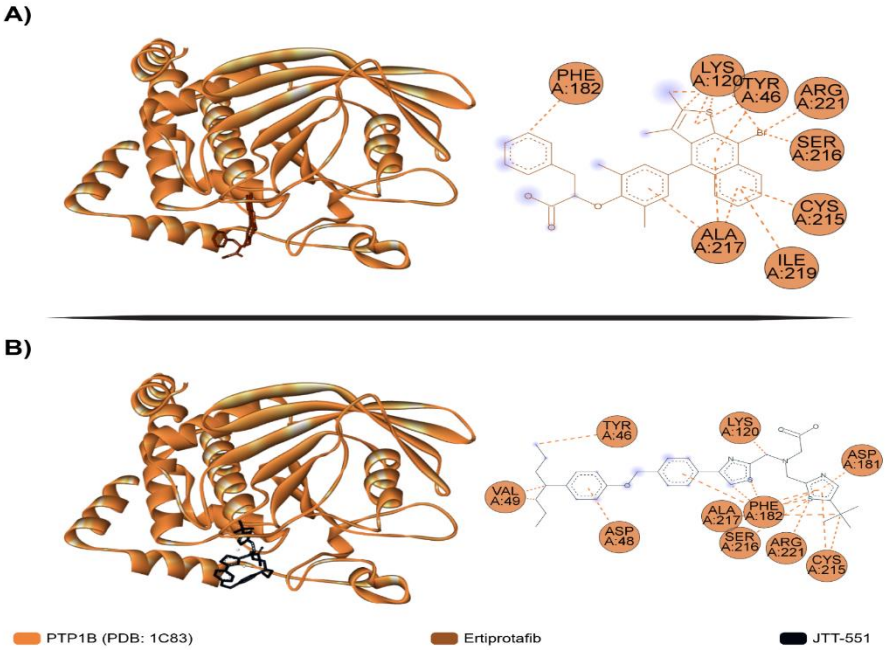
Yeniden yerleştirme ile doğrulanan protokolün bilinen etken moleküller üzerindeki performansını değerlendirmek ve sanal taramadan elde edilecek bileşikler için bir karşılaştırma ölçütü oluşturmak amacıyla, PTP1B'ye karşı geliştirilmiş ve klinik ile preklinik çalışmalara konu olmuş iki inhibitör, Ertiprotafib ve JTT-551, OAI için tanımlanan grid box koordinatları ve aynı yerleştirme parametreleri kullanılarak proteine dock edilmiştir. Ertiprotafib'in -10,4 kcal/mol bağlanma enerjisi ile katalitik cebe yerleştiği ve bromo-sübstitüe polisiklik aromatik çekirdeği üzerinden bağlanma bölgesinin merkezini işgal ettiği belirlenmiştir (Şekil 2A). Molekülün bu bölümünün Tyr46, Lys120, Cys215, Ser216, Ala217, Ile219 ve Arg221 rezidüleri ile temas kurduğu; dimetilfenil halkasının fosfat bağlayıcı P-ilmiği yüzeyine yaslanarak Ala217 ve Ile219 ile hidrofobik etkileşimler oluşturduğu gözlenmiştir. Brom atomunun Ser216 ve Arg221 rezidülerine yönelmiş konumu, ligandın P-ilmiği ile yapısal uyumunu desteklemektedir. Ligandın karşı ucunda yer alan fenil grubu ise WPD-ilmiği üzerindeki Phe182 ile aromatik istifleme etkileşimi kurarak molekülü cebin girişinde sabitlemiştir.

JTT-551 ise +15,4 kcal/mol gibi pozitif bir bağlanma enerjisi değeri vermiştir. Pozitif skor, ligandın tanımlanan arama uzayı içinde enerjetik açıdan elverişli bir yerleşim kuramadığına işaret etmektedir; bu durumun, 605,85 g/mol ağırlığındaki uzamış ve esnek molekülün OAI'ye göre kalibre edilmiş 10 × 10 × 10 Å'lık arama kutusuna sığmamasından kaynaklandığı değerlendirilmiştir. En iyi skorlu pozda molekülün tiyazol halkalarını ve karboksimetil grubunu taşıyan ucunun katalitik cebe yönelerek Lys120, Asp181, Phe182, Cys215, Ser216, Ala217 ve Arg221 rezidülerine, dallanmış alkil zincirlerini barındıran hidrofobik ucunun ise cebin girişindeki Tyr46, Asp48 ve Val49 rezidülerine komşu konumlandığı gözlenmiştir (Şekil 2B). Ancak pozitif bağlanma enerjisi nedeniyle bu poz enerjetik açıdan geçerli bir bağlanma modu olarak kabul edilmemiş ve JTT-551, sanal tarama sonuçlarının değerlendirilmesinde referans eşik olarak kullanılmamıştır. Bu sonuç, JTT-551'in literatürde karışık tip inhibisyon sergileyen ve aktif bölge dışındaki yüzeylerle de etkileşen bir molekül olarak tanımlanmasıyla uyumludur. Buna karşılık Ertiprotafib'in katalitik sistein Cys215 ve WPD-ilmiği rezidüsü Phe182 ile etkileşime girmesi, bu molekülün PTP1B'nin katalitik mekanizmasını doğrudan hedeflediğini ortaya koymaktadır. Ayrıca Tyr46, Lys120, Ser216, Ala217 ve Arg221 rezidülerinin hem yeniden yerleştirilen OAI pozunda hem de yapısal olarak OAI'den belirgin biçimde farklı olan Ertiprotafib'de ortak şekilde korunması, tanımlanan bağlanma bölgesinin PTP1B inhibisyonu için kritik olan farmakofor çekirdeğini kapsadığını göstermektedir.

Bu bulgular, kullanılan yerleştirme protokolünün katalitik cebe yönelen inhibitörleri tutarlı biçimde konumlandırabildiğini; buna karşılık aktif bölge dışına uzanan hacimli ligandlar için tanımlanan arama uzayının yetersiz kaldığını ortaya koymuştur. OAI ve Ertiprotafib için elde edilen bağlanma enerjileri, sanal tarama sonucunda öne çıkan bileşiklerin değerlendirilmesinde referans eşik olarak kullanılmıştır.



Şekil 1. PTP1B protein kristal yapısı (PDB: 1C83) içerisinde bulunan ve katalitik çekirdek ile etkileşime giren OAI inhibitörünün protein üzerindeki bağlanma profili; A) kristal yapıdaki ve yeniden kenetlenen OAI inhibitörlerinin protein içerisindeki konformasyonları, B) kristal yapıdaki OAI'nin protein ile sergilediği etkileşimler, C) yeniden kenetlenen OAI'nin protein ile sergilediği etkileşimler.



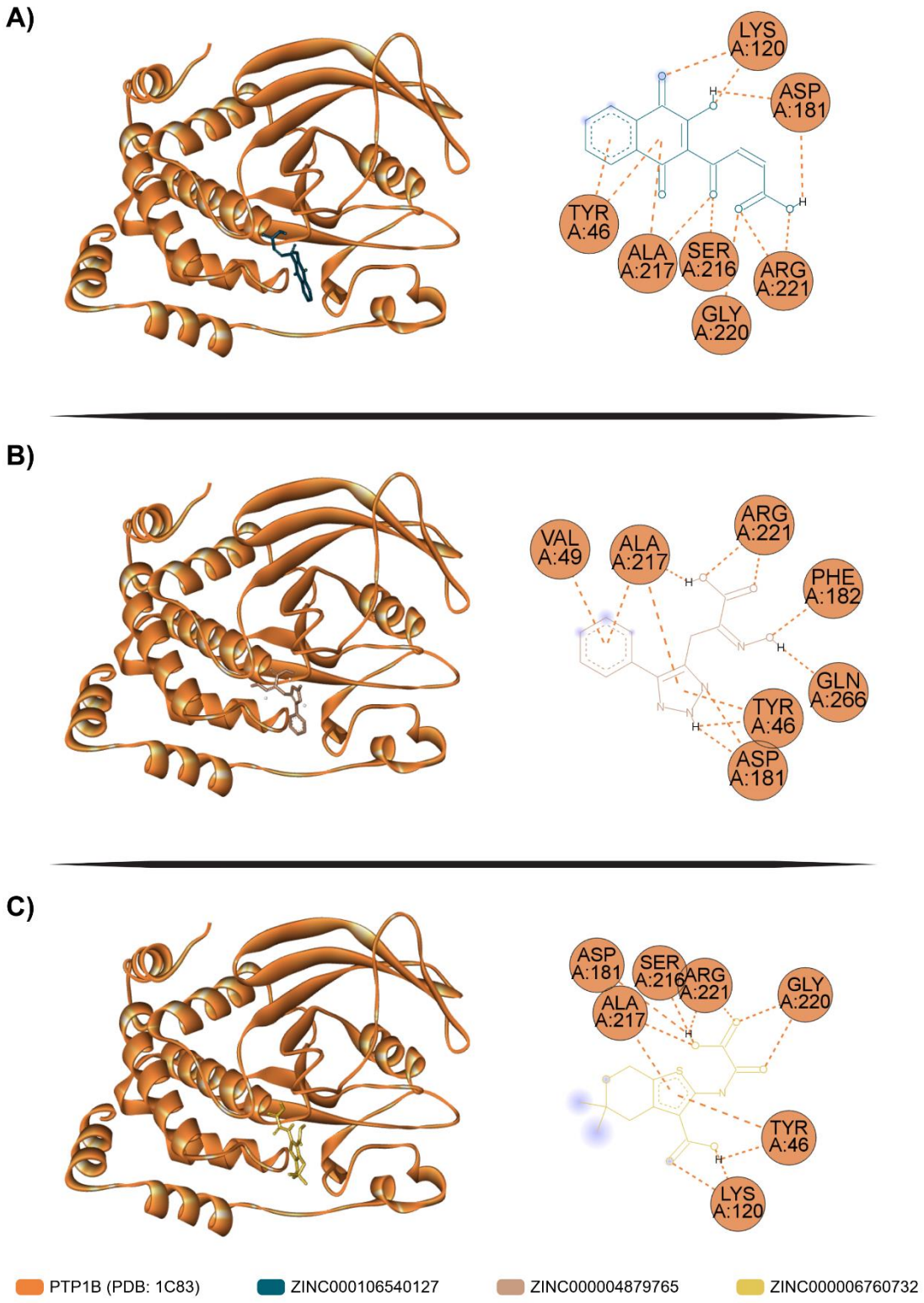
Şekil 2. Bilinen PTP1B inhibitörlerinin protein üzerindeki bağlanma profili; A) Ertiprotafib'in PTP1B katalitik çekirdeğindeki pozu, B) JTT-551'in PTP1B katalitik çekirdeğindeki pozu.

Doğrulanan bağlanma bölgesinin kimyasal gereksinimlerini sistematik biçimde tanımlamak amacıyla, OAI–PTP1B kompleksi Pharmit platformuna yüklenmiş ve ligandın katalitik cep içindeki etkileşim profilinden bir farmakofor modeli türetilmiştir. Yazılım tarafından otomatik olarak çıkarılan tanımlayıcılar arasından, ligandın karboksilat ve oksalilamino gruplarına ait beş hidrojen bağı alıcısı ile bisiklik aromatik çekirdeğe karşılık gelen bir hidrofobik özellik sorguda etkin hâle getirilmiş, her bir özellik için tolerans yarıçapı 1,0 Å olarak korunmuştur. Buna karşılık, iki negatif iyon tanımlayıcısı ve birbiriyle örtüşen iki hidrojen bağı alıcısı sorgu dışı bırakılmıştır; bu tercih, taramanın yalnızca yüklü fosfat taklidi bileşiklerle sınırlanmasını engellemek ve kimyasal çeşitliliği yüksek bir aday havuzuna ulaşmak amacıyla yapılmıştır. Oluşturulan altı noktalı farmakofor sorgusu ile ZINC Purchasable veritabanı taranmış ve tanımlanan geometrik düzeni karşılayan toplam 31.146 bileşik elde edilmiştir. Bileşikler farmakofor uyum RMSD değerlerine göre sıralandığında, en iyi uyumu gösteren adayın 0,229 Å RMSD değerine sahip olduğu belirlenmiş ve bu sonuç, sorgunun veritabanı içinde yüksek geometrik doğrulukla karşılanabildiğini ortaya koymuştur.

Farmakofor temelli olarak oluşturulan bu 31.146 bileşiklik kütüphanenin tamamı, OAI için tanımlanan ve yeniden yerleştirme ile doğrulanan grid box koordinatları kullanılarak PTP1B katalitik cebine kenetlenmiştir. Elde edilen bağlanma enerjileri ve protein–ligand etkileşim profilleri birlikte değerlendirildiğinde, -7 kcal/mol'den daha düşük bağlanma enerjisi sergileyen ve katalitik cebin kritik rezidüleriyle anlamlı temas kuran 24 bileşik umut vaat edici adaylar olarak öne çıkmıştır. Bu adaylar arasından, en düşük bağlanma enerjisine sahip olan ve aynı zamanda referans inhibitörlerin etkileşim ağını en kapsamlı biçimde tekrar eden üç bileşik — ZINC000106540127, ZINC000004879765 ve ZINC000006760732 — ileri analizler için seçilmiştir.

Seçilen bileşiklerin bağlanma modları ayrı ayrı incelendiğinde, üçünün de katalitik cebe yerleştiği ancak farklı kimyasal iskeletler üzerinden benzer bir tanıma ağı kurduğu görülmüştür. Naftokinon çekirdeği taşıyan ZINC000106540127, -8,2 kcal/mol bağlanma enerjisi ile cebe yerleşmiş; hidroksil ve karbonil grupları üzerinden Lys120 ve Asp181 ile, karboksil ucu üzerinden ise Ser216, Gly220 ve Arg221 rezidüleriyle hidrojen bağı kurmuş, aromatik çekirdeği Tyr46 ve Ala217 ile hidrofobik temas oluşturmuştur (Şekil 3A). Fenil-triazol iskeletine sahip ZINC000004879765, -8,0 kcal/mol bağlanma enerjisi göstermiş ve diğer iki bileşikten farklı bir yerleşim benimsemiştir; triazol halkası Tyr46 ve Asp181 ile etkileşirken, karboksilat grubu Ala217 ve Arg221 tarafından tutulmuş, fenil halkası Val49 ile hidrofobik temas kurmuş, imin köprüsü ise Phe182 ve Gln266 rezidülerine yönelmiştir (Şekil 3B). Tiyofen kaynaşmış bisiklik yapıdaki ZINC000006760732 ise -8,0 kcal/mol bağlanma enerjisi ile cebin en derin bölümüne yerleşmiş; amid ve karboksil grupları Asp181, Ser216, Ala217, Gly220 ve Arg221 ile yoğun bir hidrojen bağı ağı oluştururken, molekülün diğer ucundaki karboksil fonksiyonu Tyr46 ve Lys120 ile etkileşmiştir (Şekil 3C).

Üç bileşiğin etkileşim profilleri karşılaştırmalı olarak değerlendirildiğinde, Tyr46, Asp181, Ala217 ve Arg221 rezidülerinin tamamında ortak biçimde korunduğu belirlenmiştir. Bu dört rezidünün, katalitik cebin hidrofobik duvarını, WPD-ilmiğinin genel asit rezidüsünü ve fosfat bağlayıcı P-ilmiğinin iki temel bileşenini temsil etmesi, seçilen adayların PTP1B'nin katalitik mekanizmasını doğrudan hedefleyen bir bağlanma modu benimsediğine işaret etmektedir. Özellikle ZINC000106540127 ve ZINC000006760732 bileşiklerinin, birbirinden belirgin biçimde farklı kimyasal iskeletlere sahip olmalarına rağmen yeniden yerleştirilen OAI pozunun temas ettiği rezidülerin yedisini eksiksiz biçimde tekrar etmesi, farmakofor sorgusunun hedef bölgeye özgü tanıma gereksinimlerini başarıyla kodladığını göstermektedir. ZINC000004879765'in ise Phe182 ve Gln266 üzerinden cebin girişine doğru uzanarak, referans inhibitör JTT-551'in bağlanma yarığı boyunca uzanan yerleşimini andıran alternatif bir etkileşim ağı kurduğu gözlenmiştir. Bu bulgular, üç bileşiğin de bilinen PTP1B inhibitörlerinin temel farmakofor gereksinimlerini karşıladığını ve ileri değerlendirmeler için uygun adaylar olduğunu ortaya koymaktadır.



Şekil 3. Sanal tarama sonrası belirlenen 3 aday PTP1B inhibitörünün protein üzerindeki bağlanma profili; A) ZINC000106540127'nin PTP1B katalitik çekirdeğindeki pozu, B) ZINC000004879765'in PTP1B katalitik çekirdeğindeki pozu, C) ZINC000006760732'nin PTP1B katalitik çekirdeğindeki pozu.

Moleküler kenetlenme analizlerinin ardından, referans PTP1B inhibitörlerinin ilaç benzeri özelliklerini ve farmakokinetik davranışlarını öngörmek amacıyla OAI, Ertiprotafib ve JTT-551 bileşikleri SwissADME platformunda değerlendirilmiştir (Tablo 1). Fizikokimyasal parametreler incelendiğinde, üç molekül arasında belirgin bir boyut farkı dikkat çekmiştir: OAI 248,19 g/mol molekül ağırlığı ile düşük molekül ağırlıklı bir fragman niteliği taşırken, Ertiprotafib (559,51 g/mol) ve JTT-551 (605,85 g/mol) çok daha hacimli yapılar olarak öne çıkmıştır. Topolojik polar yüzey alanı değerleri sırasıyla 119,49 Å², 154,70 Å² ve 132,03 Å² olarak hesaplanmış olup, her üç bileşik de pasif membran geçişi için genel kabul gören 140 Å² eşiğine yakın veya bu eşiğin üzerinde konumlanmıştır. Lipofilisite açısından ise moleküller arasında çarpıcı bir ayrışma gözlenmiştir; OAI 0,08 gibi oldukça düşük bir Log P*o/w* değeri sergilerken, Ertiprotafib (7,79) ve JTT-551 (7,03) aşırı lipofilik karakter göstermiştir. Bu durum çözünürlük tahminlerine de doğrudan yansımış, OAI -0,02 Log S değeri ve $2{,}58\times10^{1}$ mg/ml çözünürlük ile "çözünür" sınıfında yer alırken, Ertiprotafib (-11,77; $9{,}50\times10^{-10}$ mg/ml) ve JTT-551 (-11,15; $4{,}25\times10^{-9}$ mg/ml) "çözünmez" sınıfına dahil edilmiştir.

Farmakokinetik öngörüler, fizikokimyasal profillerle uyumlu bir tablo ortaya koymuştur. OAI'nin gastrointestinal emiliminin yüksek olduğu tahmin edilirken, Ertiprotafib ve JTT-551 için düşük emilim öngörülmüştür. Üç bileşiğin de kan–beyin bariyerini geçemeyeceği belirlenmiş olup, bu bulgu periferik bir metabolik hedef olan PTP1B için istenen bir özellik olarak değerlendirilmiştir. P-glikoprotein substratlığı açısından OAI olumsuz sonuç verirken, Ertiprotafib ve JTT-551'in her ikisinin de bu taşıyıcı tarafından hücre dışına atılabileceği öngörülmüştür; bu durum, söz konusu moleküllerin hücre içi birikimini sınırlayabilecek ek bir dezavantaj oluşturmaktadır. Sitokrom P450 enzim inhibisyonu değerlendirildiğinde ise OAI'nin incelenen beş izoformun hiçbirini inhibe etmediği, Ertiprotafib'in yalnızca CYP2D6 üzerinde inhibitör etki gösterdiği, JTT-551'in ise CYP1A2, CYP2C19 ve CYP3A4 izoformlarını inhibe edebileceği tahmin edilmiştir. Bu sonuçlar, referans inhibitörlerin ilaç–ilaç etkileşimi riski taşıdığına işaret etmektedir.

İlaç benzerliği filtreleri incelendiğinde, OAI'nin Lipinski, Ghose, Veber, Egan ve Muegge kurallarının tamamını ihlalsiz biçimde karşıladığı belirlenmiştir. Buna karşılık Ertiprotafib yalnızca Veber kuralını karşılamış, diğer dört filtreden geçememiş; JTT-551 ise yalnızca Lipinski kuralını karşılayarak kalan dört filtrede başarısız olmuştur. Biyoyararlanım skorları sırasıyla 0,56, 0,85 ve 0,55 olarak hesaplanmıştır. Medisinal kimya değerlendirmesinde her üç bileşik için de PAINS uyarısı saptanmamış olması, moleküllerin deneysel tayinlerde yanlış pozitif sinyal üretme olasılığının düşük olduğunu göstermektedir; ancak hiçbiri öncü benzerliği (leadlikeness) ölçütünü karşılayamamıştır. Sentetik erişilebilirlik skorları OAI için 1,83, Ertiprotafib için 4,24 ve JTT-551 için 4,81 olarak hesaplanmış olup, yapısal karmaşıklık arttıkça sentez zorluğunun da belirgin biçimde yükseldiğini ortaya koymuştur. Bütün olarak değerlendirildiğinde, klinik ve preklinik aşamalara ulaşmış olan Ertiprotafib ve JTT-551'in aşırı lipofilik ve düşük çözünürlüklü yapılarının, ilaç benzerliği açısından ciddi sınırlamalar taşıdığı belirlenmiştir.

Tablo 1. Bilinen PTP1B inhibitörlerinin (OAI, Ertiprotafib ve JTT-551) farmakokinetik ve farmakodinamik özellilerini gösteren ADME profilleri.

ADME Profile				
Properties		**Known Inhibitors**		
Physicochemical Properties	**Inhibitor Name**	**OAI**	**Ertiprotafib**	**JTT-551**
	Chemical Formula	$C_{11}H_8N_2O_5$	$C_{31}H_{27}BrO_3S$	$C_{34}H_{43}N_3O_3S_2$
	Molecular Weight (g/mol)	248.19	559.51	605.85
	TPSA	119.49 Å²	154.70 Å²	132.03 Å²
Lipophilicity	**Log *Po*/w**	0.08	7.79	7.03
Solubility	**Log *S***	-0.02	-11.77	-11.15
	Solubility (mg/ml)	2.58e+01	9.50e-10	4.25e-09

	Solubility Class	Soluble	Insoluble	Insoluble
Pharmacokinetic Properties	**GI Absorbtion**	High	Low	Low
	BBB Permeant	No	No	No
	P-gp Substrate	No	Yes	Yes
	CYP1A2 Inhibition	No	No	Yes
	CYP2C19 Inhibition	No	No	Yes
	CYP2C9 Inhibition	No	No	No
	CYP2D6 Inhibition	No	Yes	No
	CYP3A4 Inhibition	No	No	Yes
Druglikeness	**Lipinski**	Yes	No	Yes
	Ghose	Yes	No	No
	Veber	Yes	Yes	No
	Egan	Yes	No	No
	Muegge	Yes	No	No
	Bioavailabilty Score	0.56	0.85	0.55
Medicinal Chemistry	**PAINS**	0	0	0
	Leadlikeness	No	No	No
	Synthetic Accessibility	1.83	4.24	4.81

Referans inhibitörlerin güvenlik profillerini öngörmek amacıyla aynı bileşikler ProTox 3 platformunda analiz edilmiştir (Tablo 2). Öngörülen akut toksisite değerlendirmesinde OAI ve Ertiprotafib 5. toksisite sınıfında yer alırken, JTT-551 daha toksik olan 4. sınıfta konumlanmıştır. Bu sınıflandırma, hesaplanan oral LD50 değerleriyle doğrudan uyumludur; Ertiprotafib 3000 mg/kg ile en yüksek LD50 değerini sergilerken, OAI 2025 mg/kg ile onu izlemiş, JTT-551 ise 1000 mg/kg ile üç bileşik arasında akut toksisite açısından en riskli molekül olarak öne çıkmıştır.

Organ toksisitesi öngörüleri, üç bileşik arasında farklı hedef organlara yönelen ayrışık bir risk dağılımı ortaya koymuştur. OAI için nefrotoksisite, Ertiprotafib için hem hepatotoksisite hem de nefrotoksisite, JTT-551 için ise nörotoksisite pozitif olarak tahmin edilmiştir. Solunum toksisitesinin ise üç bileşiğin tamamında pozitif çıkması dikkat çekici bulunmuştur; bu ortak bulgu, incelenen moleküllerin paylaştığı yapısal özelliklerden kaynaklanabilecek genel bir risk unsuru olarak değerlendirilmiştir. Buna karşılık, hiçbir bileşik için kardiyotoksisite öngörülmemiştir.

Toksisite son noktaları incelendiğinde, karsinojenite, immünotoksisite, mutajenite ve sitotoksisite parametrelerinin üç bileşiğin tamamında negatif olarak tahmin edilmesi, moleküllerin genotoksik ve hücresel hasar potansiyelinin düşük olduğuna işaret etmiştir. Kan–beyin bariyeri geçişi açısından Ertiprotafib ve JTT-551 için pozitif sonuç elde edilmiş olması, SwissADME tahminleriyle çelişmekte olup bu farklılık, iki platformun farklı tahmin algoritmaları ve eğitim veri setleri kullanmasından kaynaklanmaktadır. Ekotoksisite yalnızca JTT-551 için pozitif çıkarken, klinik toksisite OAI ve JTT-551 için pozitif, Ertiprotafib için negatif olarak öngörülmüştür. Beslenmeye bağlı toksisite ise yalnızca Ertiprotafib'de saptanmıştır. Bu bulgular topluca değerlendirildiğinde, referans inhibitörlerin hiçbirinin toksisite açısından tamamen temiz bir profil sergilemediği ve her birinin farklı organ sistemlerine yönelik belirgin risk taşıdığı sonucuna ulaşılmıştır.

Tablo 2. Bilinen PTP1B inhibitörlerinin (OAI, Ertiprotafib ve JTT-551) toksisite profilleri.

Toxicity Profile				
Properties		**OAI**	**Ertiprotafib**	**JTT-551**
Predicted Toksisity	**Toxicity Class**	5	5	4
	LD50 (mg/kg)	2025	3000	1000
Organ Toxicity	**Hepatotoxicity**	No	Yes	No
	Neurotoxicity	No	No	Yes
	Nephrotoxicity	Yes	Yes	No
	Respiratory Toxicity	Yes	Yes	Yes
	Cardiotoxicity	No	No	No
Toxicity End Points	**Carcinogenicity**	No	No	No
	Immunotoxicity	No	No	No
	Mutagenicity	No	No	No
	Cytotoxicity	No	No	No
	BBB-Barrier	No	Yes	Yes
	Ecotoxicity	No	No	Yes
	Clinical Toxicity	Yes	No	Yes
	Nytritional Toxicity	No	Yes	No

Sanal tarama sonucunda öne çıkan üç bileşiğin ilaç benzeri özellikleri, referans inhibitörlerle aynı protokol kullanılarak SwissADME platformunda değerlendirilmiştir (Tablo 3). Fizikokimyasal parametreler incelendiğinde, ZINC000106540127 (272,21 g/mol), ZINC000004879765 (246,22 g/mol) ve ZINC000006760732 (299,30 g/mol) bileşiklerinin tamamının düşük molekül ağırlığına sahip olduğu ve bu değerlerin OAI'nin molekül ağırlığına yakın bir aralıkta konumlandığı belirlenmiştir. Topolojik polar yüzey alanı değerleri sırasıyla 108,74 Å², 111,46 Å² ve 141,17 Å² olarak hesaplanmıştır. Lipofilisite açısından üç bileşik de 0,71–1,01 aralığında oldukça dar ve düşük Log P*o/w* değerleri sergilemiş, bu durum referans inhibitörler Ertiprotafib ve JTT-551'in aşırı lipofilik karakteriyle belirgin bir karşıtlık oluşturmuştur. Çözünürlük tahminleri de bu profili desteklemiş; Log S değerleri -1,74 ile -2,68 arasında değişen bileşiklerin üçü de "çözünür" sınıfında yer almış, hesaplanan çözünürlük değerleri $5{,}11\times10^{-1}$ ile $5{,}47\times10^{0}$ mg/ml aralığında bulunmuştur. Bu sonuç, referans inhibitörlerin pikogram düzeyindeki çözünürlük değerlerine kıyasla dokuz basamaklık bir iyileşmeye karşılık gelmektedir.

Farmakokinetik öngörüler, seçilen bileşiklerin emilim ve dağılım açısından elverişli bir profil sergilediğini ortaya koymuştur. Üç bileşiğin de gastrointestinal emiliminin yüksek olduğu tahmin

edilmiş, hiçbirinin kan–beyin bariyerini geçmeyeceği öngörülmüştür; periferik bir metabolik hedef olan PTP1B için bu kombinasyon istenen bir özellik olarak değerlendirilmiştir. Ayrıca hiçbir bileşiğin P-glikoprotein substratı olmadığı belirlenmiş, bu durum moleküllerin hücre dışına aktif taşınma yoluyla uzaklaştırılma riskinin düşük olduğuna işaret etmiştir. Sitokrom P450 enzim inhibisyonu değerlendirmesinde, ZINC000004879765 ve ZINC000006760732 bileşiklerinin incelenen beş izoformun hiçbirini inhibe etmediği; ZINC000106540127'nin ise yalnızca CYP1A2 izoformu üzerinde inhibitör etki gösterebileceği tahmin edilmiştir. Bu bulgular, seçilen adayların ilaç–ilaç etkileşimi potansiyelinin referans inhibitörlere kıyasla daha sınırlı olduğunu göstermektedir.

İlaç benzerliği filtreleri değerlendirildiğinde, ZINC000106540127 ve ZINC000004879765 bileşiklerinin Lipinski, Ghose, Veber, Egan ve Muegge kurallarının tamamını karşıladığı belirlenmiştir. ZINC000006760732 ise Lipinski ve Ghose kurallarından geçmiş, ancak yüksek polar yüzey alanı nedeniyle Veber, Egan ve Muegge filtrelerini karşılayamamıştır. Üç bileşiğin de biyoyararlanım skoru 0,56 olarak hesaplanmıştır. Medisinal kimya parametreleri incelendiğinde, ZINC000004879765 ve ZINC000006760732 için PAINS uyarısı saptanmazken, ZINC000106540127 bileşiğinde naftokinon çekirdeğinden kaynaklandığı düşünülen bir PAINS uyarısı belirlenmiştir; bu durum, söz konusu molekülün deneysel tayinlerde yanlış pozitif sinyal üretme olasılığını gündeme getirmektedir. Öncü benzerliği ölçütü ZINC000106540127 ve ZINC000006760732 tarafından karşılanmış, ZINC000004879765 bu filtreden geçememiştir. Sentetik erişilebilirlik skorları 2,82–3,24 aralığında hesaplanmış olup, referans inhibitörlerin 4,24 ve 4,81 değerlerine kıyasla daha kolay sentezlenebilir yapılar olduklarını ortaya koymuştur.

Tablo 3. Sanal tarama ile keşfedilen bileşiklerin farmakokinetik ve farmakodinamik özellilerini gösteren ADME profilleri.

ADME Profile				
Properties		**Best 3 Ligands**		
Physicochemical Properties	**ZINC ID**	**ZINC000106540127**	**ZINC000004879765**	**ZINC000006760732**
	Chemical Formula	$C_{14}H_8O_6$	$C_{11}H_{10}N_4O_3$	$C_{12}H_{13}NO_6S$
	Molecular Weight (g/mol)	272.21	246.22	299.30
	TPSA	108.74 Å²	111.46 Å²	141.17 Å²
Lipophilicity	**Log *Po*/w**	0.71	0.80	1.01
Solubility	**Log *S***	-2.09	-2.68	-1.74
	Solubility (mg/ml)	2.20e+00	5.11e-01	5.47e+00
	Solubility Class	Soluble	Soluble	Soluble
Pharmacokinetic Properties	**GI Absorbtion**	High	High	High
	BBB Permeant	No	No	No
	P-gp Substrate	No	No	No
	CYP1A2 Inhibition	Yes	No	No
	CYP2C19 Inhibition	No	No	No
	CYP2C9 Inhibition	No	No	No

	CYP2D6 Inhibition	No	No	No
	CYP3A4 Inhibition	No	No	No
Druglikeness	**Lipinski**	Yes	Yes	Yes
	Ghose	Yes	Yes	Yes
	Veber	Yes	Yes	No
	Egan	Yes	Yes	No
	Muegge	Yes	Yes	No
	Bioavailabilty Score	0.56	0.56	0.56
Medicinal Chemistry	**PAINS**	1	0	0
	Leadlikeness	Yes	No	Yes
	Synthetic Accessibility	2.82	2.83	3.24

Seçilen üç bileşiğin güvenlik profilleri ProTox 3 platformunda analiz edilmiştir (Tablo 4). Öngörülen akut toksisite değerlendirmesinde üç bileşiğin de 4. toksisite sınıfında yer aldığı belirlenmiştir. Hesaplanan oral LD50 değerleri incelendiğinde, ZINC000006760732 1500 mg/kg ile en güvenli profili sergilerken, bunu 775 mg/kg ile ZINC000004879765 ve 487 mg/kg ile ZINC000106540127 izlemiştir. Bu değerler, referans inhibitörler OAI (2025 mg/kg) ve Ertiprotafib (3000 mg/kg) ile karşılaştırıldığında daha düşük düzeyde kalmakta, ancak JTT-551'in 1000 mg/kg değeriyle benzer bir aralığı paylaşmaktadır. Organ toksisitesi öngörüleri incelendiğinde, üç bileşiğin tamamı için nefrotoksisite ve solunum toksisitesi pozitif olarak tahmin edilmiştir. Hepatotoksisite yalnızca ZINC000004879765 için pozitif çıkmış, diğer iki bileşik bu parametrede negatif sonuç vermiştir. Buna karşılık nörotoksisite ve kardiyotoksisite üç bileşiğin hiçbirinde öngörülmemiştir; bu bulgu, özellikle referans inhibitör JTT-551 için saptanan nörotoksisite riski göz önüne alındığında olumlu bir ayrışma olarak değerlendirilmiştir. Toksisite son noktaları değerlendirildiğinde, immünotoksisite ve sitotoksisite parametrelerinin üç bileşiğin tamamında negatif olarak tahmin edilmesi, moleküllerin hücresel hasar ve bağışıklık sistemi üzerindeki olumsuz etki potansiyelinin düşük olduğuna işaret etmiştir. Ancak mutajenite ZINC000106540127 ve ZINC000004879765 bileşikleri için pozitif öngörülmüş, ZINC000006760732 ise bu parametrede negatif sonuç vermiştir. Karsinojenite yalnızca ZINC000004879765 için pozitif çıkmış olup, bu bileşiğin mutajenite ve hepatotoksisite öngörüleriyle birlikte değerlendirildiğinde üç aday arasında en kritik güvenlik uyarılarını taşıdığı belirlenmiştir. Kan–beyin bariyeri geçişi ZINC000106540127 ve ZINC000004879765 için pozitif tahmin edilmiş, bu sonuç SwissADME öngörüleriyle çelişmiştir; söz konusu farklılık, iki platformun farklı tahmin algoritmaları ve eğitim veri setleri kullanmasından kaynaklanmaktadır. Ekotoksisite ve beslenmeye bağlı toksisite üç bileşiğin hiçbirinde saptanmazken, klinik toksisite ZINC000106540127 ve ZINC000006760732 için pozitif öngörülmüştür. Bu bulgular topluca değerlendirildiğinde, ZINC000006760732 bileşiğinin en yüksek LD50 değeri, mutajenite ve karsinojenite açısından temiz profili ve sınırlı organ toksisitesi ile üç aday arasında en elverişli güvenlik profiline sahip molekül olarak öne çıktığı belirlenmiştir.

Tablo 4. Sanal tarama ile keşfedilen bileşiklerin toksisite profilleri.

Toxicity Profile				
Properties		**ZINC000106540127**	**ZINC000004879765**	**ZINC000006760732**
Predicted Toksisity	**Toxicity Class**	4	4	4
	LD50 (mg/kg)	487	775	1500
Organ Toxicity	**Hepatotoxicity**	No	Yes	No
	Neurotoxicity	No	No	No
	Nephrotoxicity	Yes	Yes	Yes
	Respiratory Toxicity	Yes	Yes	Yes
	Cardiotoxicity	No	No	No
Toxicity End Points	**Carcinogenicity**	No	Yes	No
	Immunotoxicity	No	No	No
	Mutagenicity	Yes	Yes	No
	Cytotoxicity	No	No	No
	BBB-Barrier	Yes	Yes	No
	Ecotoxicity	No	No	No
	Clinical Toxicity	Yes	No	Yes
	Nytritional Toxicity	No	No	No

Çalışmada elde edilen bağlanma enerjileri tek başına değerlendirildiğinde, en güçlü skorun -10,4 kcal/mol ile Ertiprotafib'e ait olduğu görülmektedir. Ancak bu molekül, aynı zamanda klinik geliştirme sürecinde başarısız olan tek bileşiktir; söz konusu çelişki, moleküler kenetlenme skorlarının tek başına ilaç adaylığı için yeterli bir ölçüt olmadığını açık biçimde ortaya koymaktadır. Ertiprotafib'in başarısızlığının altında yatan nedenler literatürde ayrıntılı biçimde incelenmiştir. Molekülün PTP1B'ye karşı IC_{50} değeri 1,6 µM düzeyinde kalırken IκB kinaz β (IKK-β) üzerindeki IC_{50} değeri 400 nM'dir; ayrıca bileşik PPARα ve PPARγ reseptörlerini, bu reseptörlerin bilinen agonistleriyle karşılaştırılabilir konsantrasyonlarda aktive etmektedir (Erbe ve ark., 2005; Shrestha, Bhattarai, Cho, Choi ve Cho, 2007). Bir başka deyişle molekül, asıl hedefinden çok daha güçlü biçimde hedef-dışı proteinleri etkilemektedir. Buna ek olarak NMR temelli yapısal çalışmalar, Ertiprotafib'in PTP1B'yi konsantrasyona bağımlı biçimde agregasyona sürüklediğini ve klinikte gözlenen yetersiz etkinlik ile yan etkilerin bu agregasyon eğiliminden kaynaklandığını göstermiştir (Kumar, Page ve Peti, 2020). Bu davranış, çalışmamızda Ertiprotafib için öngörülen fizikokimyasal profille birebir örtüşmektedir: 7,79'luk Log *P*o/w değeri, $9{,}50\times10^{-10}$ mg/ml'lik çözünürlük ve beş ilaç benzerliği filtresinden dördünün ihlali, tipik bir agregasyon

oluşturucu profiline işaret etmektedir. Aşırı lipofilik ve çözünmeyen bileşiklerin tayin koşullarında kolloidal agregatlar oluşturarak yalancı inhibisyon sinyali üretmesi, sanal tarama ve yüksek verimli tarama kaynaklı yalancı pozitiflerin başlıca mekanizmalarından biri olarak tanımlanmıştır (McGovern, Caselli, Grigorieff ve Shoichet, 2002). Dolayısıyla Ertiprotafib'in yüksek kenetlenme skoru, gerçek bir terapötik üstünlükten ziyade molekülün hacimli ve hidrofobik yapısının skorlama fonksiyonu tarafından ödüllendirilmesinin bir sonucu olarak yorumlanmalıdır.

Bununla birlikte keşfedilen bileşiklerin de sınırlamaları bulunmakta olup bunların tartışılmadan bırakılması yanıltıcı olacaktır. Her üç aday da karboksil grubu taşımakta ve fizyolojik pH'da anyonik karakter sergilemekte; 108,74–141,17 Å² aralığındaki topolojik polar yüzey alanı değerleri de bu durumu desteklemektedir. Bu nedenle, fosfotirozin taklidi inhibitörlerin klinik ilerlemesini sınırlandıran hücre geçirgenliği sorunu (Liu ve ark., 2022) azaltılmış olmakla birlikte tümüyle ortadan kaldırılmış değildir; SwissADME'nin yüksek gastrointestinal emilim öngörüsünün Caco-2 veya PAMPA gibi deneysel geçirgenlik tayinleriyle doğrulanması gerekmektedir (Daina ve ark., 2017). Aday-özgü riskler açısından ZINC000106540127 ayrıca ele alınmalıdır: bileşik, üç aday arasında en düşük bağlanma enerjisine sahip olmasına rağmen naftokinon çekirdeği nedeniyle PAINS uyarısı almış (Baell ve Holloway, 2010), en düşük LD50 değerini (487 mg/kg) sergilemiş ve mutajenite açısından pozitif öngörülmüştür. Kinon yapılarının redoks döngüsü ve tiyol reaktivitesi gösterebilmesi, katalitik sisteini (Cys215) redoks düzenlemesine açık olan PTP1B için özel bir risk oluşturmaktadır; bu rezidünün oksidasyonu, enzimi tersinir biçimde inaktive eden fizyolojik bir mekanizmadır (Salmeen ve ark., 2003). Dolayısıyla bu bileşik için öngörülen bağlanmanın hedefe özgü olmayan bir redoks etkileşiminden kaynaklanma olasılığı göz ardı edilmemelidir. Benzer şekilde ZINC000004879765'in karsinojenite, mutajenite ve hepatotoksisite öngörülerini bir arada taşıması, bu molekülü öncelik sırasında geriye düşürmektedir. Buna karşılık ZINC000006760732; PAINS uyarısı taşımaması, öncü benzerliği ölçütünü karşılaması, 1500 mg/kg ile en yüksek LD50 değerine sahip olması ve mutajenite ile karsinojenite açısından temiz bir profil sergilemesiyle ileri çalışmalar için en güçlü aday olarak öne çıkmaktadır. Son olarak, burada sunulan tüm bulguların hesaplamalı öngörülere dayandığı vurgulanmalıdır: kenetlenme skorlama fonksiyonlarının mutlak bağlanma serbest enerjisini tahmin etmedeki doğruluğu sınırlıdır ve poz sıralama başarısı ile afinite sıralama başarısı her zaman örtüşmemektedir (Trott ve Olson, 2010; Warren ve ark., 2006); ProTox öngörüleri ise yapısal benzerlik temelli modellere dayanmaktadır (Banerjee ve ark., 2024). Bu nedenle çalışmanın devamında planlanan moleküler dinamik simülasyonları ve MM-PBSA/MM-GBSA temelli serbest enerji hesaplamaları (Genheden ve Ryde, 2015), ardından da enzim inhibisyon tayinleriyle gerçekleştirilecek deneysel doğrulama, adayların gerçek potansiyelinin belirlenmesi açısından zorunludur.

4. SONUÇ VE ÖNERİLER

Bu çalışmada, tip 2 diyabet ve obezite tedavisinde doğrulanmış bir terapötik hedef olan PTP1B enziminin katalitik bölgesine yönelik yeni inhibitör adayları, farmakofor temelli sanal tarama yaklaşımıyla araştırılmıştır. Kristal yapıda bulunan OAI inhibitörünün yeniden kenetlenmesi, tanımlanan grid box parametrelerinin ve kenetlenme protokolünün deneysel bağlanma modunu doğru biçimde yeniden üretebildiğini göstermiş, böylece taramanın yapısal temeli güvence altına alınmıştır. OAI'nin katalitik cep içindeki etkileşim profilinden türetilen altı noktalı farmakofor sorgusu ile oluşturulan 31.146 bileşiklik kütüphanenin taranması sonucunda 24 umut vaat edici bileşik belirlenmiş, bunlar arasından üçü ileri değerlendirme için seçilmiştir. Seçilen adayların, birbirinden belirgin biçimde farklı kimyasal iskeletlere sahip olmalarına rağmen katalitik cebin kritik rezidüleriyle ortak bir tanıma ağı kurmaları, farmakofor sorgusunun hedefe özgü gereksinimleri başarıyla kodladığını ortaya koymuştur. Çalışmanın en dikkat çekici bulgusu ise ham bağlanma enerjileri ile ilaç adaylığı arasındaki uyumsuzluktur: en güçlü kenetlenme skorunu sergileyen referans bileşik Ertiprotafib, aynı zamanda klinik geliştirme sürecinde başarısız olan moleküldür ve bu çalışmada da en olumsuz fizikokimyasal profili sergilemiştir. Bağlanma enerjileri molekül büyüklüğüne göre normalize edildiğinde sıralama tersine dönmüş, keşfedilen üç aday ligand etkinliği açısından referans inhibitörlerin belirgin biçimde üzerinde konumlanmıştır. Düşük molekül ağırlığı, düşük lipofilisite, yüksek çözünürlük ve yüksek gastrointestinal emilim öngörüleriyle birlikte değerlendirildiğinde bu bileşikler, PTP1B inhibitörü geliştirme çabalarının önündeki klasik farmakokinetik darboğaza karşı somut bir alternatif sunmaktadır. Toksisite öngörüleri de dikkate alındığında ZINC000006760732, güvenlik ve ilaç benzerliği ölçütlerini birlikte karşılayan en dengeli aday olarak öne çıkmıştır.

Elde edilen sonuçların hesaplamalı öngörülere dayandığı ve deneysel doğrulama gerektirdiği göz önünde bulundurulduğunda, çalışmanın devamı için bir dizi öneri sıralanabilir. Öncelikle, seçilen adayların PTP1B ile oluşturduğu komplekslerin kararlılığı yeterli uzunlukta moleküler dinamik simülasyonlarıyla incelenmeli; RMSD, RMSF ve hidrojen bağı işgal oranı analizleriyle kenetlenme pozlarının zaman içinde korunup korunmadığı sınanmalı ve MM-PBSA/MM-GBSA temelli serbest enerji hesaplamalarıyla bağlanma afiniteleri yeniden değerlendirilmelidir. Yöntemsel açıdan, OAI'ye göre kalibre edilen arama uzayının hacimli ligandlar için yetersiz kaldığı görülmüş olup, aktif bölge dışına uzanan moleküllerin değerlendirilmesinde daha geniş bir arama kutusunun veya kör kenetlenme yaklaşımının tercih edilmesi uygun olacaktır. Deneysel aşamada, rekombinant PTP1B enzimi kullanılarak inhibisyon tayinlerinin gerçekleştirilmesi, IC_{50} ve Ki değerlerinin belirlenmesi ve inhibisyon kinetiğinin aydınlatılması öncelikli hedef olmalıdır. PTP ailesi içindeki yüksek yapısal korunmuşluk göz önüne alındığında, adayların başta TCPTP olmak üzere yakın homologlara karşı seçicilik profillerinin çıkarılması kritik önem taşımaktadır. Naftokinon çekirdeği taşıyan ZINC000106540127 için ise agregasyon ve redoks kaynaklı yalancı pozitifliği dışlamaya yönelik kontrol tayinlerinin uygulanması gerekmektedir. Bu basamakları başarıyla geçen adaylar, insülin reseptörü fosforilasyonu ve glukoz alımı gibi hücresel düzeydeki işlevsel tayinlerle sınanmalı; karboksil gruplarından kaynaklanan geçirgenlik sınırlamasının aşılması amacıyla ön-ilaç (prodrug) türevlendirmeleri dâhil olmak üzere yapısal optimizasyon stratejileri değerlendirilmelidir. Son olarak, bu çalışmada öne çıkan ancak ayrıntılı biçimde incelenmeyen diğer 21 bileşiğin de aynı iş akışıyla değerlendirilmesi, aday havuzunun genişletilmesine katkı sağlayacaktır.

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HYBRID OPTIMIZATION-BASED PID DESIGN FOR AUTOMATIC VOLTAGE REGULATOR SYSTEMS

OTOMATİK GERİLİM REGÜLATÖRÜ SİSTEMLERİ İÇİN HİBRİT OPTİMİZASYON TABANLI PID TASARIMI

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Abstract
Automatic voltage regulators (AVRs) play an essential role in power systems by regulating the terminal voltage of synchronous generators and maintaining a satisfactory voltage response under operating variations and disturbances. Although proportional–integral–derivative (PID) controllers are widely employed for AVR control because of their simple structure and practical applicability, appropriate tuning of their parameters remains important for achieving favorable stability characteristics together with satisfactory transient performance. In this study, a recently developed two-stage hybrid controller design method based on spectral abscissa and integral absolute error (IAE) optimization is utilized for the optimal tuning of a PID controller with a derivative filter for an AVR system. The conventional linearized AVR model consisting of amplifier, exciter, generator, and sensor subsystems is considered, and the proportional, integral, derivative, and derivative-filter parameters are treated as design variables. In the first stage, the controller parameters are determined by minimizing the spectral abscissa of the closed-loop system. Since the spectral abscissa corresponds to the largest real part of the closed-loop poles, its minimization aims to shift the dominant dynamics further into the left-half complex plane and thereby increase the exponential decay rate of the system. However, spectral abscissa minimization alone does not explicitly account for time-domain performance characteristics. Therefore, in the second stage, the IAE of the terminal-voltage error is minimized to improve the transient performance. The second-stage optimization is initialized using the controller obtained from the first stage and is performed subject to a spectral abscissa constraint, allowing improvement of the voltage response while limiting deterioration of the favorable stability characteristics achieved previously. The effectiveness of the proposed design framework will be investigated through numerical simulations, with emphasis on the closed-loop spectral properties and transient terminal-voltage response.
Keywords: Automatic voltage regulator, PID controller, spectral abscissa, integral absolute error, optimization

Özet
Otomatik gerilim regülatörleri (AVR'ler), senkron generatörlerin terminal gerilimini düzenleyerek ve işletme koşullarındaki değişimler ile bozucular altında uygun bir gerilim cevabı sağlayarak güç sistemlerinde önemli bir rol oynamaktadır. Oransal–integral–türev (PID) denetleyiciler, basit yapıları ve pratik uygulanabilirlikleri nedeniyle AVR kontrolünde yaygın olarak kullanılmakla birlikte, elverişli kararlılık özellikleri ile tatmin edici geçici rejim performansının birlikte elde edilebilmesi için denetleyici parametrelerinin uygun şekilde ayarlanması önemini korumaktadır. Bu çalışmada, AVR sistemi için türev filtresine sahip bir PID denetleyicinin optimal olarak ayarlanmasında, spektral apsis ve integral mutlak hata (IAE) optimizasyonuna dayalı yakın zamanda geliştirilmiş iki aşamalı hibrit bir denetleyici tasarım yöntemi kullanılmaktadır. Yükselteç, uyartım sistemi, generatör ve sensör alt sistemlerinden oluşan klasik doğrusallaştırılmış AVR modeli ele alınmakta; oransal, integral, türev ve türev filtresi parametreleri tasarım değişkenleri olarak kabul edilmektedir. İlk aşamada, denetleyici parametreleri kapalı çevrim sisteminin spektral apsisi minimize edilerek belirlenmektedir. Spektral apsis, kapalı çevrim kutuplarının en büyük reel kısmına karşılık geldiğinden, bu büyüklüğün minimize edilmesi baskın dinamiklerin karmaşık düzlemin sol yarı bölgesinde daha sola taşınmasını ve böylece sistemin üstel sönüm hızının artırılmasını amaçlamaktadır. Bununla birlikte, yalnızca spektral apsisin minimize edilmesi zaman alanındaki performans özelliklerini doğrudan dikkate almamaktadır. Bu nedenle ikinci aşamada, geçici rejim performansını iyileştirmek amacıyla terminal gerilimi hatasının IAE değeri minimize edilmektedir. İkinci aşamadaki optimizasyon, ilk aşamadan elde edilen denetleyici kullanılarak başlatılmakta ve spektral apsis kısıtı altında gerçekleştirilmektedir.

Böylece, daha önce elde edilen elverişli kararlılık özelliklerindeki bozulma sınırlandırılırken gerilim cevabının iyileştirilmesi hedeflenmektedir. Önerilen tasarım çerçevesinin etkinliği, kapalı çevrim spektral özellikleri ve terminal geriliminin geçici rejim cevabı üzerine odaklanılarak sayısal benzetimler aracılığıyla incelenecektir.

Anahtar kelimeler: Otomatik gerilim regülatörü, PID denetleyici, spektral apsis, integral mutlak hata, optimizasyon

ANN BASED GENERALIZED PREDICTIVE CONTROL OF A DC MOTOR UNDER DISTURBANCE

BOZUCU ETKİ ALTINDAKİ BİR DC MOTORUN YAPAY SİNİR AĞI TEMELLİ GENELLEŞTİRİLMİŞ ÖNGÖRÜLÜ KONTROLÜ

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Abstract
This paper presents an Artificial Neural Network (ANN)-based Generalized Predictive Control (GPC) scheme for a DC motor under external disturbance. To account for system disturbance, ANN model is utilized to capture the time-varying dynamics online, predicting the future system outputs directly from observed input-output data. Using these predictions, the GPC algorithm calculates control inputs over a predefined future horizon and applies the signal corresponding to the current time step. The ANN parameters are tuned using gradient descent with an adaptive learning rate (ALR), which guarantees model convergence while ensuring controller stability. The proposed approach demonstrates robust control performance in simulation under disturbance condition. It outperforms a standard PID controller in comparative evaluation. This study cen be generalized to GPC of any particular type of DC motor as well.
Keywords: Artificial neura network, Generalized predictive control, DC motor, PID control

Özet
Bu çalışma, harici bozucu etki altındaki bir DC motor için Yapay Sinir Ağı (artificial neural network-ANN) tabanlı bir Genelleştirilmiş Öngörülü Kontrol (generalized predictive control-GPC) yöntemi sunmaktadır. Sistemdeki bozucu etkiyi hesaba katmak amacıyla YSA modeli, zamana bağlı olarak değişen dinamikleri çevrimiçi (online) olarak yakalamak ve gözlemlenen girdi-çıktı verilerinden doğrudan gelecekteki sistem çıktılarını tahmin etmek için kullanılmaktadır. GPC algoritması, bu tahminleri kullanarak önceden belirlenmiş bir gelecek ufku boyunca kontrol girdilerini hesaplar ve mevcut zaman adımına karşılık gelen sinyali sisteme uygular. ANN parametreleri, modelin yakınsamasını ve kontrolün kararlılığını garanti eden uyarlamalı öğrenme adımlı gradyan inişi (gradient descent) yöntemi kullanılarak güncellenmektedir. Önerilen yaklaşım, bozucu etki koşulu altındaki benzetimde gürbüz bir kontrol performansı sergilemektedir. Karşılaştırmalı değerlendirmelerde standart bir PID denetleyiciden daha iyi performana sahip olduğu gözlemlenmiştir. Bu çalışma, herhangi bir özel DC motor tipinin GPC kontrolüne de genelleştirilebilir.
Anahtar kelimeler: Yapay sinir ağı, Genelleştirilmiş tahminli kontrol, DC motor, PID kontrol

KALSİNE MARN KATKILI ÇİMENTOLAR İLE ÜRETİLEN MİKRO-BETONLARIN YANGIN DAYANIMI

FIRE RESISTANCE OF MICRO-CONCRETES PRODUCED WITH CALCINED MARL-BLENDED CEMENTS

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ÖZET
Portland çimentosunun artan küresel üretimi ve CO_2 emisyonlarını azaltmaya yönelik acil ihtiyaç, katkılı çimento üretiminin artırılmasını zorunlu kılmıştır. Son dönemde, kalsine killer bu talebi karşılamak adına oldukça umut verici malzemeler olarak öne çıkmıştır. Bu çalışma, kalsine marn katkılı çimento içeren mikro-betonların yüksek sıcaklığa maruz kaldıklarında sergiledikleri davranışı incelemektedir. %0, %10, %20 ve %30 ikame oranlarında kalsine marn içeren katkılı çimentolar kullanılarak dört farklı karışım hazırlanmıştır. Mikro-betonların özgül ağırlık, su emme, eğilme ve basınç dayanımı değerleri belirlenmiştir. Mikro-betonların yüksek sıcaklık altındaki performansını değerlendirmek amacıyla 300 °C, 600 °C ve 800 °C sıcaklık seviyeleri kullanılmıştır. Deneysel sonuçlar, alternatif bir puzolan olan kalsine marn katkılı çimentolarla üretilen mikro-betonların eğilme ve basınç dayanımlarının, %20 ikame oranına kadar artış gösterdiğini ortaya koymuştur. Ayrıca, puzolanik özellikli kalsine marn kullanımının, yüksek sıcaklık koşullarında mikro-betonların yangın direnci üzerinde olumlu bir etkiye sahip olduğu tespit edilmiştir. Mikro-beton numuneleri için sağlanan bu olumlu sonuçların yanı sıra, söz konusu katkılı çimentolarla çimento içeriğinin en aza indirilmesi, son derece sürdürülebilir ve uygun maliyetli bir üretim süreci sağlamaktadır.
Anahtar kelimeler: Kalsine Marn, Katkılı Çimento, Puzolan, Yangın Dayanımı.

ABSTRACT
The increasing global production of Portland cement and the urgent need to mitigate CO_2 emissions have necessitated a rise in the production of blended cements. Recently, calcined clays have emerged as highly promising materials to address this demand. This study investigates the behavior of micro-concretes containing calcined marl blended cement under high-temperature exposure. Four different mixtures were prepared using blended cements containing calcined marl at replacement levels of 0%, 10%, 20%, and 30%. The density, water absorption, and flexural-compressive strength values of the micro-concretes were determined. To evaluate the performance of the micro-concretes under high temperatures, exposure levels of 300 °C, 600 °C, and 800 °C were utilized. The experimental results revealed that the flexural and compressive strengths of the micro-concretes produced with blended cements containing the alternative pozzolan, calcined marl, increased up to a replacement level of 20%. Furthermore, it was determined that the incorporation of calcined marl had a positive effect on the fire resistance of the micro-concretes under elevated temperature conditions. Besides these positive outcomes for micro-concrete specimens, minimizing cement content with these blended cements ensures a highly sustainable and cost-effective production process.
Keywords: Calcined Marl, Blended Cement, Pozzolan, Fire Resistance.

GİRİŞ
Küresel enerji güvenliğine yönelik endişeleri gidermenin hızlı, maliyetsiz ve uygulanabilir yolu enerji tasarrufudur. Kalkınmakta olan ülkeler, enerji ithalatını azaltmak için enerji yoğun sektörlerde tasarruf politikalarına yönelmektedir. Bu sektörlerin başında gelen inşaat alanında ise üretimi maliyetli ve yüksek emisyonlu olan çimentoya bağımlılık kritik bir sorundur. Çimentoya alternatif olarak doğal puzolan kullanımı, üretimi ekonomik ve çevreci hale getirirken betonun performansını da artırmaktadır (Erdal, 2026). Türkiye, zengin doğal puzolan rezervleriyle sürdürülebilir çimento ve beton üretimi açısından oldukça yüksek bir potansiyeline sahiptir (Beniz, 2022).

Puzolanlar**,** en genel anlamıyla kendi başlarına bağlayıcılık özelliği taşımayan, ancak çimento inceliğinde öğütüldüklerinde içerdikleri reaktif silis ve alümin bileşenleri sayesinde, çimento hidratasyonu ürünü olan kalsiyum hidroksit ($Ca(OH)_2$) ile reaksiyona girerek hidrolik bağlayıcılık karakteristiği kazanan malzemelerdir. Bu puzolanik reaksiyon, matris yapısını yoğunlaştırarak nihai ürünün dayanım ve dayanıklılığını artırır. Literatürde killerin 600 °C – 900 °C sıcaklık aralığında kalsine edildiklerinde yüksek puzolanik aktivite gösterdikleri de bilinmektedir (Daştan, 2005).
Puzolan kullanılarak üzetilen betonların dayanım ve dayanıklılıklarındaki artışa bağlı olarak onların yangın dayanımlarının da iyileştiği literatürden bilinmektedir (Karaca ve ark., 1997). Puzolanlar, betonun yüksek sıcaklık altındaki performansını iki temel mekanizmayla iyileştirir: İlki, termal olarak kararsız olan ve 400 °C üzerinde bozunarak hacimsel çatlaklara yol açan kalsiyum hidroksit ($Ca(OH)_2$) kristallerini puzolanik reaksiyonla tüketerek daha kararlı C-S-H jellerine dönüştürmesidir. İkincisi ise, oluşturduğu yoğun ve hidrolik yapısı sayesinde ısı iletimini yavaşlatması ve mikrodolgu etkisiyle yüksek sıcaklık kaynaklı termal gerilmeleri sönümlemesidir (Lublóy ve ark., 2017).
Literatürde yaygın olarak kullanılan mineral katkıların yüksek sıcaklık performansları incelendiğinde; silis dumanının oluşturduğu aşırı yoğun matris yapısı sebebiyle yangın anında yüksek iç buhar basıncına maruz kalarak patlamalı çatlamalara yol açabildiği bilinmektedir. Uçucu kül ise küresel tanecik yapısıyla ısıl gerilmeleri sönümlemede başarılı olsa da erken yaş reaksiyon hızı düşüktür. Buna karşın, metakaolin gibi kalsine killer hem yüksek puzolanik aktivitesi sayesinde ($Ca(OH)_2$)'i hızla tüketmekte hem de yüksek sıcaklıklarda termal olarak daha kararlı amorf alüminosilikat fazları oluşturmaktadır. Bu durum, kalsine killeri yüksek yangın dayanımı hedeflenen beton tasarımlarında diğer puzolanlara göre daha avantajlı bir konuma getirmektedir (Kushnir ve ark., 2021; Lublóy ve ark., 2017; Morsy ve ark., 2007).
Doğal marn, kil ve kalkeri bir arada bulunduran, kalkerin %30-50 ve kilin %50-70 oranlarında karışımından oluşan, bir kayaç türüdür. Genellikle %30 kil ve %70 kalker içeren marnlar çimento yapımında kullanılırlar (Özer, 2024). Geleneksel çimento klinkerinin kalsinasyon sıcaklığına kıyasla çok daha düşük bir seviyede (yaklaşık 800 °C) kalsine edilerek puzolanik aktivite kazanan doğal marnlar, aynı zamanda kolay öğütülebilir yapıları sayesinde katkılı çimento üretimi için de yüksek bir potansiyel sunmaktadır. Literatürde kalsine marnların çimento ve beton endüstrisinde kullanılabilirliği üzerine oldukça yeni ve güncel çalışmalar mevcut olmakla birlikte, bu malzemelerin yüksek sıcaklık ve yangın dayanımı üzerindeki performansını inceleyen kapsamlı bir çalışma henüz bulunmamaktadır.

Betonun yüksek sıcaklıklara maruz kaldığında uğradığı mekanik performans kayıpları dikkate alındığında, bu çalışmanın temel hedefleri şunlardır:

- Yerel ve doğal puzolan rezervlerinin aktif hale getirilmesiyle sürdürülebilir malzeme çeşitliliğinin artırılması,
- Katkılı çimento ve beton endüstrisinde doğal puzolan kullanımının yaygınlaştırılmasına katkı sağlanması,
- Yangın riski yüksek yapılar için betonun termal direncini artıracak tasarım optimizasyonlarının gerçekleştirilmesi,
- Nihai olarak, literatürde kullanımı oldukça yeni ve umut vadeden kalsine marn katkılı çimento ile üretilen betonların yangın dayanımlarının iyileştirilmesidir.

MATERYAL VE YÖNTEM

Bu çalışmada hedeflenen yüksek yangın dayanımlı beton tasarımlarının optimize edilmesi amacıyla deneysel bir yöntem izlenmiştir. Yöntem, yerel kaynaklardan elde edilen doğal marnların kalsinasyon sürecinin ardından kalsine marn katkılı çimento üretimi, mikro-beton numunelerinin hazırlanması, yangın deneyleri ve performans değerlendirme aşamalarını içermektedir. Üretilen mikro-betonların farklı sıcaklıklar altındaki mekanik davranışları standart test yöntemleri ile incelenmiştir. Çalışmada kullanılan malzemelere ilişkin bazı tanımlamalar aşağıda verilmektedir.
Mikro-betonların imalatında kullanılacak katkılı çimento üretimlerinde Portland çimentosu ile ağırlıkça %10, 20 ve 30 oranlarında yerdeğiştirme malzemesi olarak optimum sıcaklıkta (800 °C) kalsine edilmiş Sinop ili, Erfelek ilçesinden elde edilen kalsine marn kullanılmıştır. Portland çimentosu (CEM 42.5 R) Ünye Çimento A.Ş'den temin edilmiştir. Doğal marnın puzolanik aktivitesini belirlemek için TS 25' in önerdiği mekanik deney yöntemi kullanılmış ve standardın aktivite minimum sınır değeri (>4MPa) ölçütünü 8.10MPa olarak sağlamıştır. Optimum kalsinasyon sıcaklığında (800 ^{0}C) kalsine edilen marnın

puzolonik aktivite değeri, mekanik deney yöntemi olan kireç-doğal puzolan karışımlı numunelerin 7 günlük basınç dayanımları ile belirlenmiştir. Çalışmada kullanılan Portland çimentosu ve doğal marn ait bazı özellikler Tablo 1-2 de verilmektedir.

Tablo 1. Portland Çimentosuna ait Bazı Özellikler

Kimyasal	**(%)**	**Fiziksel ve Mekanik Özellikler**			
SiO_2	19.53	Özgül ağırlık, (g/cm^3)	3.12		
Al_2O_3	5.33	Priz başı, (saat)	2.50		
Fe_2O_3	3.56	Priz sonu, (saat)	4.15		
CaO	62.26	Hacim genleşmesi, (mm)	2.00		
MgO	0.99	Blaine (cm^2/g)	3210		
SO_3	3.02	Basınç dayanımları	2 gün	7 gün	28 gün
Kızdırma kaybı	3.06	(MPa)	32.30	44.60	53.00

Tablo 2. Doğal Marnın Bazı Özellikleri

Kimyasal	**(%)**	**Fiziksel özellikler**	
SiO_2	56.63	Özgül ağırlık, (g/cm^3)	2.70
Al_2O_3	12.34	Blaine (cm^2/g)	4630
Fe_2O_3	7.46	Puzolanik aktivite (MPa)	
CaO	12.91	7 günlük basınç	8.10
MgO	2.83	dayanımı	

Mikro-betonların üretiminde kullanılan ince agrega, Gümüşhane ili, Torul ilçesinden temin edilmiştir. Mikro-betonların üretiminde kullanılan agregalara ilşkin granülometrik dağılım Tablo 3' de ve agregaların doygun kuru yüzeyli (DKY), kuru ve görünür özgül ağırlıkları ve su emme değerleri ise TS EN 1097-6' e uygun olarak belirlenerek Tablo 4' de verilmektedir. Çimento inceliğinin altında öğütülen kalsine marnın inceliğinin oluşturduğu karışımların kıvam sabitliğini sağlamak ve daha homojen dağılımlı çimento taneleri elde etmek için polikarboksilat eter tipi hiperakışkanlaştırıcı kullanılmıştır. Akışkanlaştırıcının özgül ağırlığı 1.05 gr/cm^3 tür. Mikro-betonların karışım suyu bileşeni olarak içme suyu kalitesinde Ordu ili, Altınordu ilçesine ait şebeke suyu kullanılmıştır. Mikro-betonlara ait bileşen miktarları Tablo 5' de verilmektedir.

Tablo 3. Agregaların Granülometrik Dağılımı

Granülometrik Dağılım					
Elek çapı (mm)	4-2	2-1	1-0,5	0,5-0,25	0,25-0
(%)	40	20	15	15	10

Tablo 4. Agregaların Özgül Ağırlıkları ve Su Emme Değerleri

Elek çapı (mm)	**Özgül Ağırlıklar (g/cm^3)**			**Su Emme (%)**
	Kuru	**DKY**	**Görünür**	
(4 - 1)	2.69	2.70	2.71	0.33
(1 - 0)	2.63	2.67	2.72	1.18

Tablo 5. Mikro-Betonlara Ait Bileşen Miktarları

Bileşenler (kg/m^3)	**PC**	**CM10**	**CM20**	**CM30**
Portland Çimentosu	450	405	360	315
Kalsine Marn	-	45	90	135
Su	225	225	225	225
Toplam Agrega	1350	1350	1350	1350
Akışkanlaştırıcı	3.60	4.50	4.73	4.95

Karışımlara taze haldeyken mini-çökme deneyi yapılmıştır. Ardından 40 x 40 x 160 mm boyutlarındaki prizmatik kalıplara yerleştirilmiştir. 24 saat sonunda kalıplarından çıkarılan numuneler etiketlenerek kür tankına yerleştirilmiştir. Mikro-betonlara ait bazı görünümler Şekil 1' de verilmektedir.



Şekil 1. Mikro-betonların üretim sonrası görünümleri

Deney numunelerine yangın etkisini belirlemek amacı ile yangın deneyleri başlamadan önce 40x40x160 mm'lik prizmatik numuneler önce 24 saat süresince 70 ^{o}C' de etüvde bırakılarak sabit numune ağırlıkları elde edilmiştir. Daha sonra numuneler fırın sıcaklık artış hızı 5-10 ^{o}C/dk olan yüksek sıcaklık fırınına yerleştirilmişlerdir. Deney programındaki sıcaklıklar (300 ^{0}C – 600 ^{0}C – 800 ^{0}C) elde edildikten sonra numuneler fırında 1 saat süresince bırakılmışlardır. Yangın deneyleri tamamlandıktan sonra yüksek sıcaklık fırınından çıkarılan mikro-beton numuneler havada ve suda soğutma koşulları ile soğutulmuşlardır. Her iki koşul altındaki tüm numuneler oda sıcaklığına getirilmişlerdir. Mikro-beton numunelerin TS EN 196-1' e uygun eğilme-basınç dayanımları tespit edilmiştir. Elde edilen deney sonuçları, yangın etkisinde bırakılmayan geleneksel numunelerin sonuçları ile karşılaştırılmıştır. Yangın etkisinde kalmış mikro-beton numunelerinin genel görünümleri Şekil 2' de verilmektedir.



Şekil 2. Yangın Etkisinde Kalmış Mikro-Beton Numuneler ve Yüksek Sıcaklık Fırını

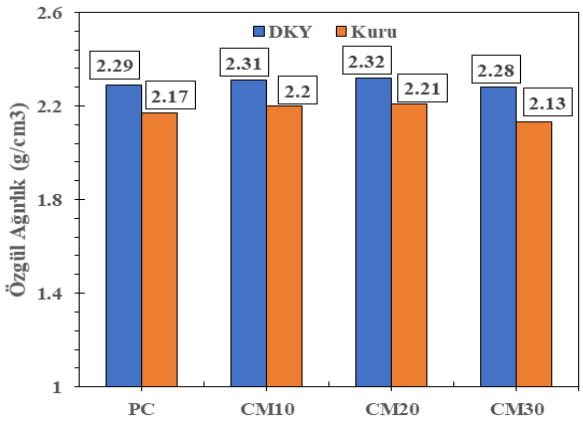
ARAŞTIRMA BULGULARI VE TARTIŞMA

Kalsine marn içeren katkılı çimentolar kullanılarak üretilen mikro-beton numuneler üzerinde yukarıda açıklanan yöntemlere göre gerçekleştirilen deneylerden elde edilen bulgular ve tartışmalar aşağıda verilmektedir.

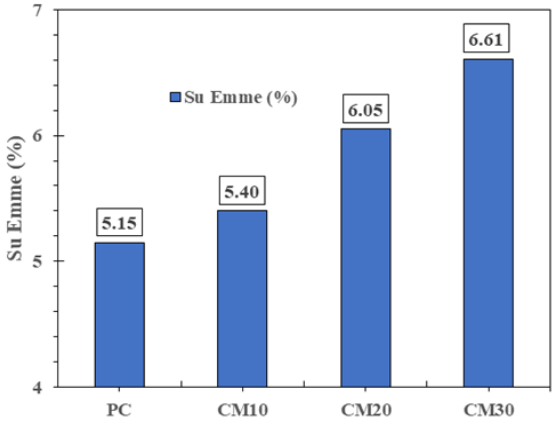
Mini Çökme, Özgül Ağırlık ve Su Emme

Mini slump deneyi sonucunda mikro-betonların her bir karışımı için çökme değerleri yaklaşık olarak 20-30 mm civarında tespit edilmiştir. Mikro-betonların doygun kuru yüzeyli (DKY) ve kuru özgül ağırlıkları ve su emme değerleri Şekil 3-4' de verilmektedir.

Mikro-betonların (CM10, CM20, CM30) DKY özgül ağırlıkları, Portland çimentosununkine göre sırasıyla %0,9, %1,3 artmış, %0,4 azalmış ve kuru özgül ağırlıkları ise sırasıyla %1,4, %1,8 artmış, %1,9 azalmıştır. Bu değişimler, mikro-betonları oluşturan bileşenlerin özgül ağırlıklarına bağlı olarak meydana gelmektedir. Mikro-betonların (CM10, CM20, CM30) su emme değerleri, Portland çimentosununkine göre sırasıyla %4,9, %17,5, %28,3 artmıştır. Bu değişimler ise, kalsine marnın inceliğinin Portland çimentosununkine göre daha yüksek olması ile ilişkilidir.



Şekil 3. DKY- Kuru Özgül Ağırlıklar



Şekil 4. Su Emme Değerleri

Katkılı Çimentoların Fiziksel Özellikleri

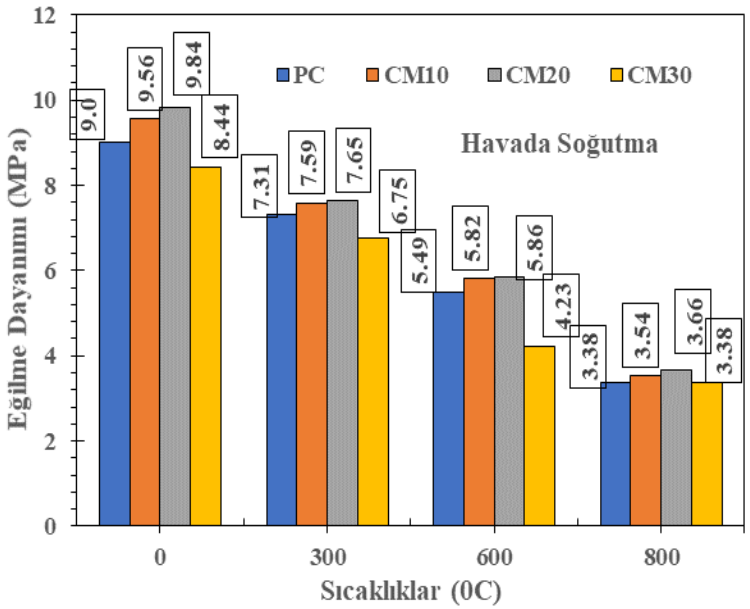
Çalışmada kullanılan kalsine marn içeren katkılı çimentoların bazı fiziksel özellikleri Tablo 6' da verilmektedir. Katkılı çimentoların Blaine incelikleri, Portland çimentosununkine göre sırasıyla %2,96, %10,28, %12,46 artmıştır. Diğer bir değişle, katkılı çimentoların incelikleri marnın inceliğine bağlı olarak azalmıştır. Katkılı çimentoların özgül ağırlıkları, Portland çimentosununkine göre sırasıyla %5,8, %9,9, %10,6 azalmıştır. Katkılı çimentoların özgül ağırlıklarındaki azalma marnın özgül ağırlığındaki azalmaya bağlıdır.

Tablo 6. Katkılı Çimentoların Fiziksel Özellikleri

Fiziksel özellikler	**PC**	**CM10**	**CM20**	**CM30**
Blaine inceliği (cm^2/g)	3210	3305	3540	3610
Özgül Ağırlık (g/cm^3)	3.12	2.95	2.84	2.82

Eğilme - Basınç Dayanımları Bulguları

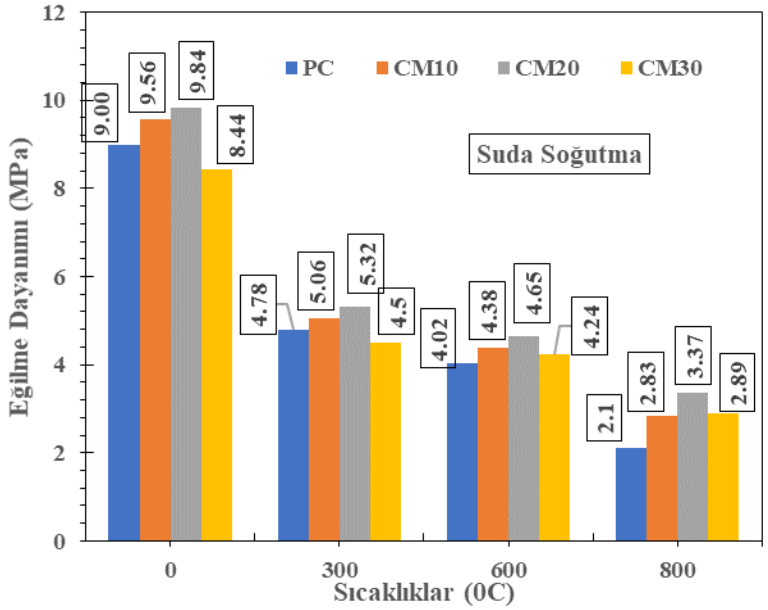
Çalışmada üretilen mikro-betonların yangın deneyleri sonrası eğilme-basınç dayanımları havada ve suda soğutma koşullarına göre sırasıyla Şekil 5-8'de verilmektedir.



Şekil 5. Mikro-Betonların Yangın Deneyleri Sonrası Eğilme Dayanımları (Havada Soğutma)

Yüksek sıcaklık maruziyeti sonrasında havada soğutulan numunelerin eğilme dayanımı gelişimleri incelendiğinde; 300 °C ve 600 °C maruziyetlerinde CM10 ve CM20 serilerinin, referans (PC)

numunesine kıyasla daha yüksek bir termal direnç gösterdiği ve eğilme dayanımlarını daha iyi koruduğu görülmüştür. Bu durum, literatür ile uyumlu olarak (Ibrahim ve ark., 2012), kalsine marnın puzolanik aktivitesi sonucu oluşan yoğun C-S-H matrisinin ve serbest kireç tüketiminin olumlu bir sonucudur. Ancak 800 °C sıcaklığa ulaşıldığında tüm serilerde keskin bir dayanım kaybı kaydedilmiştir. Literatürle uyumlu olan bu düşüş (Lublóy ve ark., 2017); 700 °C'nin üzerindeki sıcaklıklarda betona asıl dayanımı veren C-S-H jellerinin kimyasal olarak tamamen dehidrasyona uğrayarak bozunması ve agregadaki kuvars faz dönüşümü kaynaklı mikroskobik çatlak ilerlemeleri ile açıklanmaktadır. Buna rağmen, 800 °C'de bile CM10 (3.54 MPa) ve CM20 (3.66 MPa) serilerinin geleneksel PC serisine (3.38 MPa) göre daha yüksek dayanım sergilemesi, optimize edilmiş kalsine marn ikamesinin yüksek sıcaklıklarda yapısal bütünlüğü korumadaki başarısını ortaya koymaktadır.

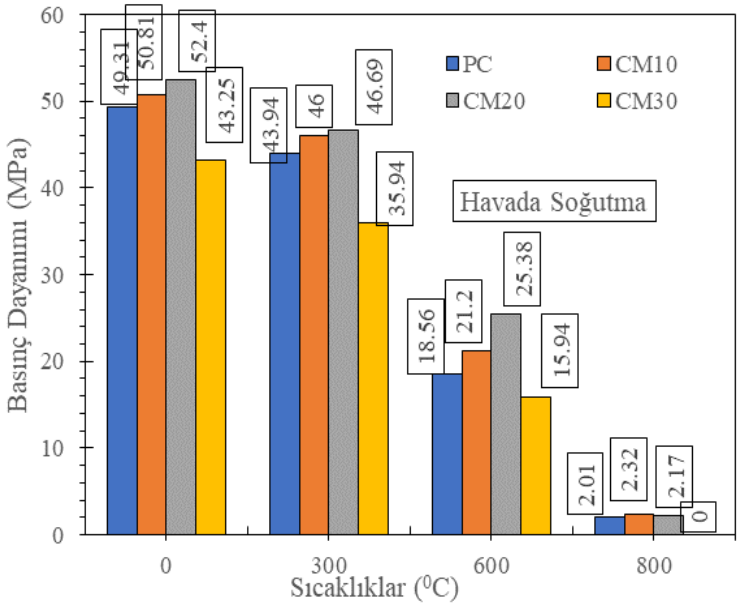


Şekil 6. Mikro-Betonların Yangın Deneyleri Sonrası Eğilme Dayanımları (Suda Soğutma)

Yüksek sıcaklık maruziyeti sonrasında suda soğutulan numunelerin eğilme dayanımı gelişimleri incelendiğinde; kalsine marn ikamesinin matris performansına olan pozitif etkisi bu zorlu koşul altında da net bir şekilde gözlenmiştir. 300 °C, 600 °C ve 800 °C sıcaklık aşamalarının tamamında, %10 (CM10) ve %20 (CM20) kalsine marn içeren seriler, referans (PC) numunesine kıyasla daha yüksek eğilme dayanımı değerleri sergilemiştir. Özellikle 800 °C gibi ileri seviye ısıl yıkımın gerçekleştiği aşamada, PC numunesinin eğilme dayanımı 2.10 MPa'ya düşerken, CM20 numunesi 3.37 MPa ile en yüksek direnci ortaya koymuştur. Suda soğutma koşullarında puzolanik katkının sağladığı bu avantaj, literatürde belirtildiği gibi (Kushnir ve ark., 2021), kalsine killerin matris içindeki serbest kalsiyum hidroksiti ($Ca(OH)_2$) önceden tüketmesiyle doğrudan ilişkilidir. Nitekim yüksek sıcaklıkta kalsiyum oksite dönüşen serbest kireç, suyla ani temas anında hızla dehidrasyona uğrayarak şiddetli hacimsel genleşmelere ve içsel patlamalara yol açmaktadır. CM10 ve CM20 serilerinde bu zayıf faz puzolanik reaksiyonla ortadan kaldırıldığı için, matris ani su temasını daha az hasarla atlatmıştır. Ancak ikame oranının %30'a yükseltilmesi (CM30), bağlayıcı faz dengesini olumsuz etkilediğinden tüm sıcaklıklarda dayanımın tekrar düşmesine neden olmuştur.

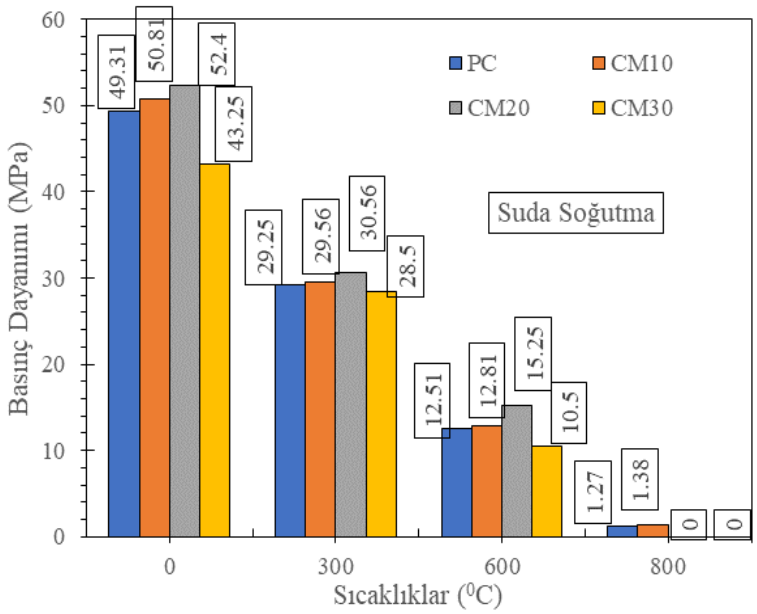
Soğutma yöntemlerinin betonun termal davranışı üzerindeki etkisini belirlemek amacıyla, havada soğutma ve suda soğutma rejimleri karşılaştırmalı olarak analiz edilmiştir. Elde edilen tüm veriler, soğutma tekniğinin eğilme dayanımı üzerinde belirleyici bir rol oynadığını ve suda soğutulan numunelerin havada soğutulanlarınkine kıyasla çok daha radikal güç kayıplarına uğradığını göstermektedir. Örneğin 300 °C' de havada soğutulan PC numunesi 7.31 MPa değerini koruyabilirken, suda soğutulduğunda bu değer 4.78 MPa'ya gerilemiştir. Benzer bir eğilim kalsine marn katkılı serilerde de görülmüş, ancak kalsine marn içeren numuneler bu kaybı sınırlamada daha başarılı olmuştur. Suda soğutmanın yarattığı bu ek yıkım, ani sıcaklık düşüşünün beton matrisinde şiddetli termal gerilmeler (termal şok) üretmesinden kaynaklanmaktadır. Eğilme dayanımı, yapısı gereği mikroskobik çatlak

ilerlemelerine karşı basınç dayanımından çok daha hassastır. Dolayısıyla, suda ani soğutma esnasında matris ile agrega arayüzünde oluşan mikro çatlak şebekeleri, suda soğutulan serilerin eğilme dayanımını doğrudan ve keskin bir biçimde aşağı çekmiştir.



Şekil 7. Mikro-Betonların Yangın Deneyleri Sonrası Basınç Dayanımları (Havada Soğutma)

Yüksek sıcaklık maruziyeti sonrası havada soğutulan numunelerin basınç dayanımı sonuçları incelendiğinde; kalsine marn katkısının betonun eksenel yük taşıma kapasitesi üzerindeki olumlu etkisi, oda sıcaklığından itibaren kendini göstermiştir. Oda sıcaklığında en yüksek basınç dayanımı 52.40 MPa ile %20 kalsine marn içeren CM20 serisinde elde edilmiş; bu seriyi 50.81 MPa ile CM10 takip ederek şreferans (PC) numunesini (49.31 MPa) geride bırakmıştır. Bu durum, literatürde de belirtildiği gibi (Danner ve ark., 2018), kalsine marnın yüksek puzolanik aktivitesi sayesinde mikro boşlukları doldurarak daha yoğun bir jel (C-S-H) yapısı meydana getirmesinin doğrudan bir sonucudur.
Sıcaklık artışıyla birlikte tüm serilerde dayanım kayıpları gözlenmiş, ancak bu kayıpların oranları seriler arasında farklılık göstermiştir. 300 °C ve özellikle 600 °C maruziyetlerinde CM10 ve CM20 serileri, referans PC numunesine kıyasla dikkate değer ölçüde daha iyi korumuştur. 600 °C'de PC numunesinin dayanımı %62.3 oranında radikal bir kayıpla 18.56 MPa'ya gerilerken; CM20 serisi 25.38 MPa, CM10 serisi ise 21.20 MPa değerlerini korumayı başarmıştır. Bu kritik aşamadaki puzolanik avantaj, literatürde de belirtildiği gibi (Danner ve ark., 2018), kalsine killerin matristeki termal olarak kararsız kalsiyum hidroksit ($Ca(OH)_2$) kristallerini erkenden tüketerek yapıyı 400°C – 600°C aralığındaki dehidrasyon çatlaklarından koruması ile açıklanmaktadır. Ancak 800 °C sınırına ulaşıldığında, tüm serilerin basınç dayanımlarında tam bir yapısal çöküş (yıkım) kaydedilmiştir. Bu aşamada PC, CM10 ve CM20 serileri 2.01 ile 2.32 MPa arasında değişen sembolik dayanım değerlerine düşerken, %30 kalsine marn içeren CM30 serisi yük taşıma kabiliyetini tamamen kaybederek 0 MPa değerini almıştır. Literatürle tam bir uyum gösteren bu ileri düzey yıkım (Lublóy ve ark., 2017); 700 °C'nin üzerinde ana bağlayıcı faz olan C-S-H jellerinin kimyasal yapısının tamamen bozulması, matris bütünlüğünün yok olması ve agreganın gösterdiği şiddetli termal genleşmeler sonucu oluşan makro çatlaklar ile ilişkilendirilmektedir. Ayrıca aşırı puzolan ikamesine sahip CM30 serisinin yüksek sıcaklık kararsızlığı, optimize edilmemiş yüksek mineral katkı oranlarının ısıl gerilmeler altındaki kırılganlığını net bir şekilde ortaya koymaktadır.



Şekil 8. Mikro-Betonların Yangın Deneyleri Sonrası Basınç Dayanımları (Suda Soğutma)

Yüksek sıcaklık maruziyeti sonrasında suda soğutulan numunelerin basınç dayanımı performansları incelendiğinde; ani sıcaklık düşüşünün (termal şok) yarattığı yapısal tahribat tüm serilerde kendisini net bir şekilde göstermiştir. 300 °C ve 600 °C sıcaklık aşamalarında, %10 (CM10) ve %20 (CM20) kalsine marn içeren seriler, referans (PC) numunesine kıyasla daha yüksek bir eksenel yük taşıma kapasitesi sergilemiştir. Özellikle 600 °C maruziyetinde PC numunesinin dayanımı 12.51 MPa'ya gerilerken, CM20 serisi 15.25 MPa değerini koruyarak en yüksek kararlılığı ortaya koymuştur. Bu sıcaklık kademelerindeki puzolanik avantaj, literatürde (Barauskas, 2020), kalsine killerin boşluk doldurma (mikrodolgu) kabiliyeti ve matrisi daha kompakt hale getiren ikincil C-S-H jelleri sayesinde, su temasıyla oluşan ani çekme gerilmelerine karşı iç yapının daha dirençli kalabilmesi ile açıklanmaktadır. Ancak 800 °C sınırına gelindiğinde, suda soğutma rejiminin yıkıcı etkisi numune matrisini tamamen işlevsiz hale getirmiştir. Bu ileri sıcaklık derecesinde PC (1.27 MPa) ve CM10 (1.38 MPa) serileri sembolik dayanım değerlerinde kalırken; %20 ve %30 kalsine marn içeren CM20 ve CM30 serileri yük taşıma kabiliyetlerini tamamen yitirerek 0 MPa değerini almıştır. Literatür verileriyle desteklenen bu durum (Morsy ve ark., 2007); 800 °C'de zaten kimyasal ve fiziksel olarak bağlayıcılığını bütünüyle yitirmiş, C-S-H yapısı bozunmuş olan beton matrisinin, suyla temas ettiği anda şiddetli bir buhar basıncına ve ısıl gerilmeye maruz kalmasından kaynaklanmaktadır. Yüksek mineral katkı oranına sahip CM20 ve CM30 serilerinin daha gevrek yapısı, bu ani faz değişimi ve termal şok altında mikro/makro çatlakların hızla ilerlemesine yol açarak numunelerin bütünlüğünü tamamen kaybetmesine neden olmuştur.

Soğutma rejimlerinin basınç dayanımı üzerindeki etkileri karşılaştırıldığında; suda soğutma tekniğinin, havada soğutmaya kıyasla tüm serilerde ve sıcaklıklarda çok daha agresif bir dayanım kaybına yol açtığı görülmüştür. Örneğin, 300 °C'de havada soğutulan PC numunesi 43.94 MPa değerini koruyabilirken, suda soğutulduğunda bu değer %33.4'lük bir düşüşle 29.25 MPa'ya gerilemiştir. Benzer şekilde 600 °C'de havada 25.38 MPa basınç dayanımı gösteren CM20 serisi, suda soğutulduğunda 15.25 MPa değerine düşmüştür. Basınç dayanımındaki bu radikal farklar; sıcak beton matrisinin suyla ani teması esnasında oluşan yüksek termal gradyanların, betonun dış kabuğu ile çekirdeği arasında şiddetli gerilmelere (termal şok) neden olmasından kaynaklanmaktadır. Bu fiziksel gerilmeler, matris genelinde yoğun bir mikro çatlak ağı oluşturarak eksenel yük taşıma kapasitesini doğrudan aşağı çekmiştir.

SONUÇLAR

Bu çalışma kapsamında, yerel ve doğal puzolan rezervlerinin aktif hale getirilerek çimento-beton sektöründe kullanımının yaygınlaştırılması ve kalsine marn katkılı betonların yüksek sıcaklık/yangın

altındaki performans sınırlarının belirlenmesi hedeflenmiştir. Deneysel veriler ve yapılan analizler doğrultusunda aşağıdaki temel sonuçlara ulaşılmıştır:

- Kalsine marnın çimento matrisindeki optimum kullanım oranının %20 (CM20) olduğu belirlenmiştir. Hem oda sıcaklığında (52.40 MPa basınç ve 9.84 MPa eğilme dayanımları olarak) hem de yüksek sıcaklık maruziyetlerinde en yüksek mekanik performans CM20 serisinde elde edilmiştir.
- 300 °C ve özellikle 600 °C sıcaklık kademelerinde CM10 ve CM20 serileri, referans (PC) numunesine göre daha yüksek bir kararlılık sergilemiştir. Bu durum, kalsine marnın puzolanik reaksiyonu sayesinde termal olarak kararsız olan ($Ca(OH)_2$) (kalsiyum hidroksit) kristallerini erkenden tüketmesi ve daha kararlı ikincil C-S-H jelleri oluşturması ile açıklanmaktadır.
- Suda soğutma (termal şok) rejimi, havada soğutmaya kıyasla tüm serilerde ve sıcaklıklarda çok daha agresif mekanik performans kayıplarına yol açmıştır. Su temasıyla oluşan ani termal gradyanlar, matris genelinde yoğun bir mikro çatlak dağılımının meydana geldiği düşünülmektedir.
- Yangın söndürme senaryolarını simüle eden 800 °C suda soğutma koşullarında; şahit (PC) numunesi 2.10 MPa eğilme dayanımına gerilerken, CM20 serisi 3.37 MPa değerini koruyarak referansa göre yaklaşık %60 daha yüksek performans göstermiş ve kalsine marnın çatlak ilerlemesini sınırlandırmadaki başarısını kanıtlamıştır.
- 800 °C sınırına ulaşıldığında, beton matrisindeki ana bağlayıcı faz olan C-S-H jellerinin kimyasal olarak tamamen dehidrasyona uğraması ve agreganın kuvars faz dönüşümü kaynaklı genleşmesi nedeniyle genel bir yapısal çöküş kaydedilmiştir. Bu ileri sıcaklık aşamasında, yüksek kalsine marn katkı oranına sahip CM30 serisi her iki soğutma rejiminde de, CM20 serisi ise suda soğutma altında yük taşıma kabiliyetini tamamen yitirerek "0" MPa basınç dayanımı değeri almıştır.
- Geleneksel çimento klinkerine kıyasla oldukça düşük bir sıcaklıkta (yaklaşık 800 °C) kalsine edilerek puzolanik aktivite kazanan yerel kalsine marnın beton endüstrisinde kullanımı; hem küresel enerji tasarrufu ve düşük karbon emisyonu hedeflerini desteklemekte hem de yüksek yangın riskli yapılar için optimize edilmiş, ekonomik ve güvenli bir tasarım alternatifi sunmaktadır.

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A PHYSICS-CONSTRAINED REDUCED-ORDER FRAMEWORK FOR TAFONI-INSPIRED GRADED GYROID TPMS TURBINE-BLADE COOLING: MORPHOLOGY MAPPING, LITERATURE BENCHMARKING, AND ROBUST DESIGN SCREENING

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Abstract
High turbine inlet temperatures place severe thermal demands on gas-turbine hot-section components, while the compressor bleed required for cooling reduces cycle performance. This study develops a physics-constrained reduced-order model (ROM) for a tafoni-inspired graded gyroid triply periodic minimal surface (TPMS) cooling concept. The aim is to provide a conservative, literature-benchmarked screening method for use before high-fidelity CFD or experiments. A thresholded Gray-Scott morphology is quantified using void fraction, local feature width, and interface density, and these descriptors are mapped to gyroid cell size and level-set threshold. The sheet-gyroid solid and its two complementary fluid labyrinths are defined explicitly so that porosity, specific area, hydraulic diameter, mass flow, and energy balances remain consistent. Internal heat transfer is represented with an experimental sheet-gyroid Nusselt correlation, while low-Reynolds-number pressure-loss trends are compared with published TPMS data. Film extraction is treated with explicit coolant mass and enthalpy conservation, and film and porous-effusion modes are not used together on the same surface element.
The ROM was checked against analytical solutions. The axial energy solution shows first-order convergence, the normalized energy residual remains at machine precision, and the expected limits are recovered for vanishing and large coolant flow, vanishing TBC resistance, and zero blowing. Sensitivity and uncertainty analyses identify gyroid cell size, gas-side heat-transfer coefficient, and the transferred gyroid Nusselt level as the main sources of local response variation; together they account for approximately 91% of the variance in the screening surrogate. The nominal coolant requirement of 0.768 g/s increases to about 1.12 g/s at the 95th percentile when independent ±20% epistemic uncertainties are imposed. In a controlled load-matched graded-gyroid surrogate with approximately equal porosity and internal area, the model hotspot falls by 18.7 K and the required coolant decreases by 8.3% relative to a uniform gyroid. This controlled comparison is interpreted as a ROM mechanism test. The operating state is classified as mixed heat-transfer/coolant-capacity controlled, with hydraulic loss providing an additional design constraint.
Keywords: tafoni; gyroid; TPMS; turbine-blade cooling; reduced-order model; transpiration cooling; film cooling; robust design; biomimetic design.

1. Introduction
Higher turbine inlet temperatures can increase specific work and cycle efficiency, but they also raise the thermal load on metallic hot-section components. Current cooling systems therefore combine internal convection, thermal-barrier coatings (TBCs), film cooling, double-wall cooling, and increasingly complex additively manufactured internal geometries [1-5]. Because the coolant is usually extracted from the compressor, additional cooling increases the aerodynamic and thermodynamic burden on the engine. The design problem is thus to keep the metal below a prescribed temperature while limiting both coolant consumption and pressure loss [1,4].
Film cooling remains a major external-cooling method, but its performance depends on jet-in-crossflow behavior, density and momentum ratios, hole geometry, pressure gradients, surface curvature, turbulence, and downstream mixing [2,3,28,29]. Shaped holes can improve surface coverage and reduce jet lift-off [3]. Conventional discrete-hole systems, however, provide cooling at separated locations, and the resulting distribution need not follow the non-uniform heat load of a turbine airfoil.
Additive manufacturing has enlarged the range of internal-cooling geometries that can be produced. Triply periodic minimal surfaces (TPMS), in particular, provide continuous bicontinuous pathways, high interfacial area per unit volume, and adjustable porosity [6-10]. Gyroid and related TPMS structures can increase heat transfer relative to conventional channels, but the gain is accompanied by a pressure-loss penalty that becomes important at low Reynolds number [7-10]. Recent turbine studies have applied

TPMS concepts to trailing-edge lattices, leading-edge effusion, and double-wall cooling [13-15]. These studies also indicate that topology, porosity, wall thickness, and pressure loss need to be considered together.

Transpiration cooling provides another way to distribute coolant over a heated surface. In a porous wall, the coolant absorbs heat within the structure before reaching the external surface, reducing the heat load imposed on the wall [11,12,25-27]. Experiments with gyroid transpiration coupons show that injection ratio is a useful comparison parameter and that increasing porosity does not necessarily improve area-averaged effectiveness at a fixed injection ratio [11]. Numerical and experimental work on non-uniform permeability also shows that directing more coolant toward regions of higher heat load can improve thermal uniformity [12,25]. These findings provide a basis for considering graded architectures rather than simply increasing porosity.

The biomimetic basis for the geometry is tafoni, a class of cavernous weathering forms containing spatially varying cavities, ribs, and connected voids. Previous studies have related tafoni development to salt weathering, moisture transport, dynamical instability, and self-organization [20-23]. Computational biomimetic work has also used tafoni morphology as an input for generative architectural design [24]. There is, however, no established evidence that a tafoni-derived turbine-cooling structure outperforms a conventional TPMS. The geometry is therefore described here as tafoni-inspired, and the synthetic morphology is treated as a design input rather than a reproduction of natural rock-weathering physics.

The framework links morphology generation and measurement with a phase-consistent sheet-gyroid definition, literature-based TPMS heat-transfer and pressure-loss relations, and explicit coolant mass and enthalpy balances. Film and porous-effusion boundary modes are kept separate, while sensitivity, epistemic uncertainty, regime mapping, and analytical code checks are used to identify physically credible screening states. Quantitative findings are labeled by evidence source—verification, literature benchmark, ROM prediction, or hypothesis—so that preliminary screening is not confused with CFD or experimental validation.

2. Methodology

2.1. Tafoni-inspired morphology generation

The Gray-Scott reaction-diffusion system is used as a *morphology generator*, not as a complete physical model of tafoni weathering. The two interacting scalar fields are governed by

$$\frac{\partial u}{\partial t} = D_u \nabla^2 u - uv^2 + F(1-u) \qquad (1)$$

$$\frac{\partial v}{\partial t} = D_v \nabla^2 v + uv^2 - (F+k)v \qquad (2)$$

The Gray-Scott family is a well-established pattern-forming reaction-diffusion model [16-19]. Here it serves as a controllable generator of labyrinthine patterns with spatial variation resembling the selected tafoni features.

Figure 1 presents the thresholded morphology used for the screening analysis, the local two-dimensional void-fraction map, and a representative sheet-gyroid section obtained after morphology matching. The pattern is used quantitatively: its measured descriptors provide the inputs for the subsequent geometry mapping.

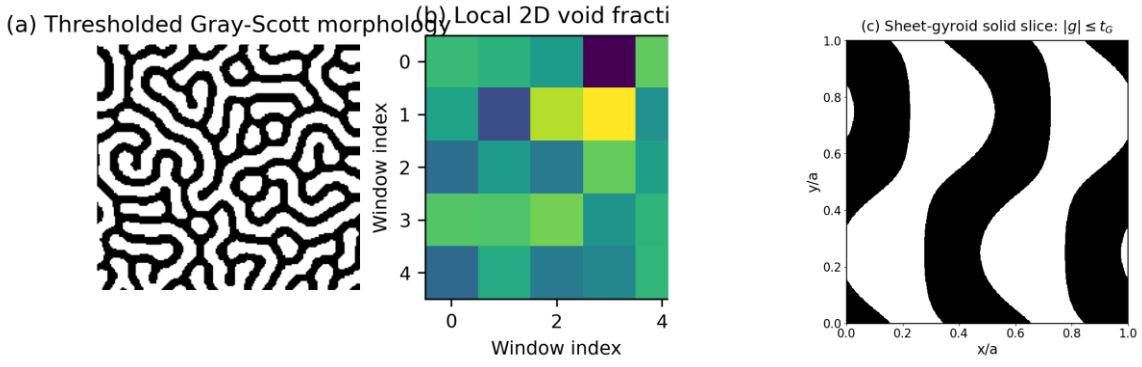


Figure 1. Quantified morphology-to-gyroid mapping. (a) Thresholded Gray–Scott pattern used as a tafoni-inspired morphology generator, (b) local two-dimensional void fraction, and (c) a representative

sheet-gyroid solid section at the morphology-matched threshold. In panel (c), black denotes the solid sheet $|g| \leq tG$ and white denotes the two complementary fluid labyrinths.

The two-dimensional void-area fraction is

$$A_A = \frac{A_{void}}{A_{total}} \qquad (3)$$

The measure in Eq. (3) refers to the two-dimensional morphology and should not be interpreted as a three-dimensional porosity measure. For the selected thresholded pattern, the value is approximately 0.46. Sampling with local 5×5 windows gives a coefficient of variation of approximately 6%, while the distance-transform/skeleton analysis gives a mean local void width of about 6.4 pixels, a median of 6.3 pixels, and an approximate 10th–90th percentile range of 5.7–8.0 pixels. These quantities are used for relative mapping only.

2.2. Gyroid definition and phase consistency

The physical gyroid coordinates are scaled through the unit-cell length a_G:

$$X = \frac{2\pi x}{a_G}, \qquad Y = \frac{2\pi y}{a_G}, \qquad Z = \frac{2\pi z}{a_G} \qquad (4)$$

The nodal gyroid approximation is [6]

$$g(X,Y,Z) = \cos X \sin Y + \cos Y \sin Z + \cos Z \sin X \qquad (5)$$

For a sheet thickness controlled by a level-set threshold tG, the solid sheet is defined by $|g| \leq tG$, while the two complementary fluid labyrinths occupy $g > tG$ and $g < -tG$, respectively.

$\Omega_s = \{|g| \leq t_G\}, \quad \Omega_{f+} = \{g > t_G\}, \quad \Omega_{f-} = \{g < -t_G\}$ (6)

The phase definition keeps the solid sheet and the two complementary fluid labyrinths mutually exclusive. Porosity and flow area are computed from the fluid domain actually used in the calculation. A single-labyrinth design therefore uses only one fluid region, whereas a dual-labyrinth sheet-gyroid design uses their combined fluid volume.

For the selected fluid domain, the geometric descriptors are

$$\varepsilon = \frac{V_f}{V_{tot}}, \qquad S_v = \frac{A_{sf}}{V_{tot}}, \qquad D_h = \frac{4\varepsilon}{S_v} \qquad (7)$$

The 2D-to-3D conversion is treated as a morphology-matching rule rather than a stereological validation. Numerical integration of the gyroid field with the sheet definition in Eq. (6) gives a combined dual-labyrinth void fraction $\varepsilon_{map} \approx 0.457$ at $tG \approx 0.830$, matching the present 2D target $AA \approx 0.457$. The local morphology envelope corresponds approximately to $tG \approx 0.75$–0.89.

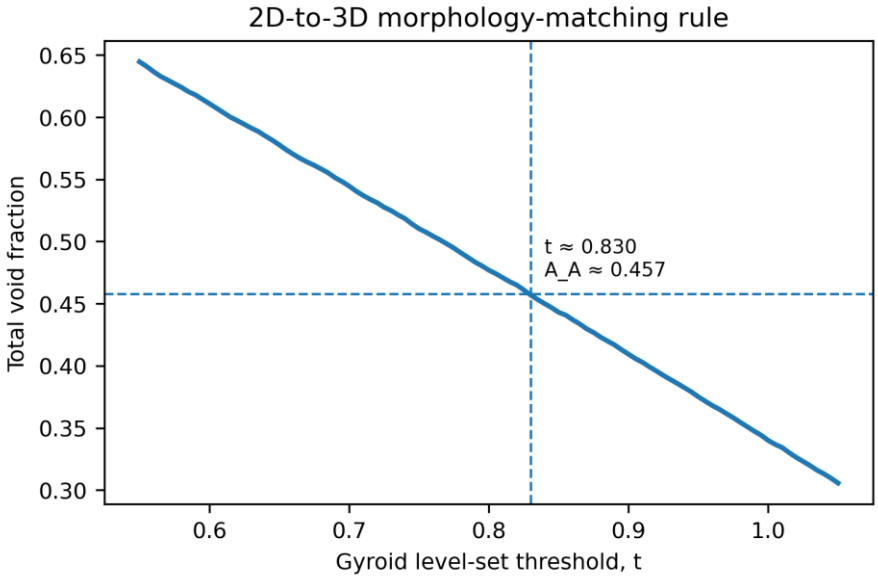


Figure 2. Numerical morphology-matching relation between the sheet-gyroid level-set threshold and the total void fraction. The dashed lines show the present 2D design target and the corresponding 3D gyroid threshold.

The local characteristic morphology width $d_T(\mathbf{x})$ is mapped to a graded gyroid cell size through

$$a_G(\mathbf{x}) = a_0 \frac{d_T(\mathbf{x})}{\overline{d}_T} \qquad (8)$$

The local-width mapping transfers relative spatial scale while preserving the morphology-mapping mean cell size aG,0 = 2.5 mm. For the present synthetic pattern, the resulting local cell-size range is approximately 2.28–2.78 mm; this modest variation does not support a claim of strongly multiscale grading.

Reference geometry convention. Three geometry levels are kept distinct. (i) The morphology-matched geometry uses aG,0 = 2.5 mm, tG ≈ 0.830, and εmap ≈ 0.457 for the two fluid labyrinths combined, with aG ≈ 2.28–2.78 mm. (ii) The generic ROM screening uses ε0 = 0.50 and aG = 2.0–2.5 mm as independent screening assumptions rather than morphology-derived values. (iii) The controlled grading mechanism test uses aG,0 = 2.5 mm with γ = 0.20, producing aG ≈ 2.08–3.04 mm at nearly fixed porosity and integrated internal area. Unless otherwise stated, ε denotes the combined fluid fraction of the two complementary labyrinths; a single-labyrinth implementation must recompute ε and the corresponding flow area.

2.3. Flow variables

For a reference cross-sectional envelope WH, the superficial and interstitial velocities are distinguished as

$$u_{sf} = \frac{\dot{m}}{\rho WH}, \qquad U_i = \frac{u_{sf}}{\varepsilon} \qquad (9)$$

The hydraulic Reynolds and Prandtl numbers are

$$Re_H = \frac{\rho U_i D_h}{\mu}, \qquad Pr = \frac{\mu c_p}{k_f} \qquad (10)$$

2.4. Thermal-resistance and coolant-energy model

The external gas convection, TBC conduction, metal conduction, and internal convection are represented by a series ROM:

$$R_g = \frac{1}{h_g A_e}, \quad R_{TBC} = \frac{t_{TBC}}{k_{TBC} A_e}, \quad R_m = \frac{t_m}{k_m A_c}, \quad R_i = \frac{1}{h_i A_i} \qquad (11)$$

This one-dimensional resistance network is a screening approximation and does not replace three-dimensional conjugate heat conduction in an actual blade.

The nodal heat transfer and coolant update are

$$q_i = \frac{T_{g,eff,i} - T_{c,i}}{R_g + R_{TBC} + R_m + R_i} \qquad (12)$$

$$h_{c,i+1} = h_{c,i} + \frac{q_i}{\dot{m}_i} \qquad (13)$$

With constant coolant heat capacity for verification, the enthalpy update reduces to the corresponding temperature-increment form.

2.5. Literature-informed internal heat-transfer closure

The primary gyroid heat-transfer closure is the experimental sheet-gyroid correlation of Reynolds et al. [9]:

$$Nu_G = 0.49 Re_H^{0.62} Pr^{0.4}, \qquad 100 < Re_H < 2500 \qquad (14)$$

The Reynolds et al. correlation is the primary literature-based internal heat-transfer relation used in the ROM; it was obtained from experimental TPMS heat-exchanger measurements over 100 < ReH < 2500 [9].

Iyer et al. [10] reported a lower-Reynolds-number gyroid trend at a substantially different Prandtl number. Its exponent is consequently retained for trend comparison, while its absolute correlation is not transferred to the present case:

$Nu_{I,*} = Nu_G(Re_0)\,(Re_H/Re_0)^{0.57}$, $Re_0 = 200$ (15)

For the low-Re comparison, only the published Reynolds-number exponent is retained, while the magnitude is anchored to the experimental air-side relation at the reference point.

For pressure-loss screening, the Iyer low-Re gyroid Fanning relation is converted to a Darcy factor:

$$f_D = 4 f_F = 62 Re_H^{-0.58} \qquad (16)$$

The Iyer pressure-loss relation is used only within its reported Reynolds-number range and for relative screening.
The corresponding pressure drop is

$$\Delta p = f_D \frac{L}{D_h} \frac{\rho U_i^2}{2} \qquad (17)$$

Figure 3 compares the three relations used in the thermal screening. The Reynolds correlation is the primary experimental relation, the Iyer curve provides a low-Reynolds-number trend check, and the Hausen relation is included only as a straight-channel reference.

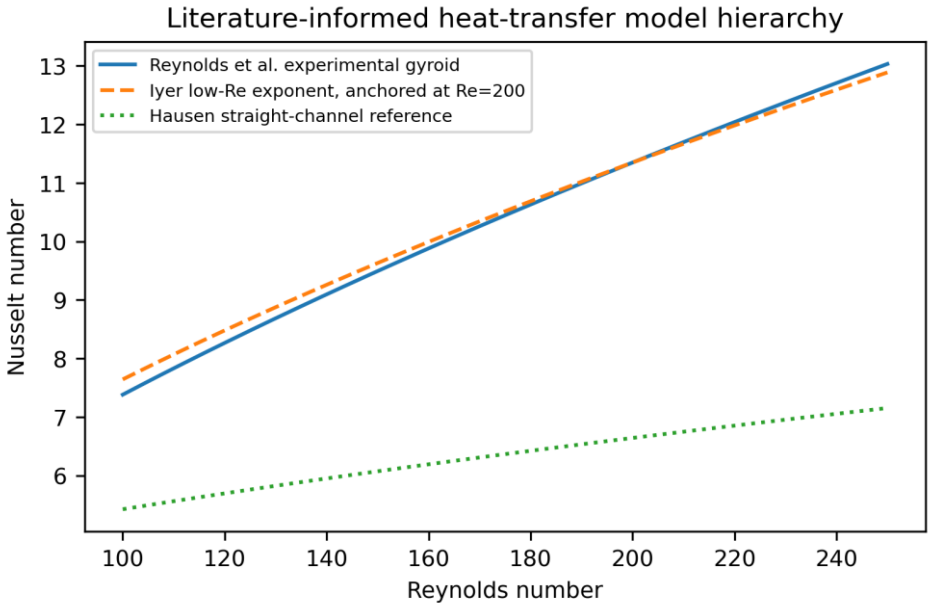


Figure 3. Heat-transfer model hierarchy. Reynolds et al. is the primary experimental gyroid relation; the anchored Iyer curve tests low-Re trend sensitivity; Hausen [30] is shown only as a straight-channel reference.

2.6. Energy-consistent discrete film model

Film extraction must remove mass from the internal coolant path:

$$\dot{m}_{i+1} = \dot{m}_i - \dot{m}_{f,i} \qquad (18)$$

The adiabatic wall temperature is represented by

$$T_{aw} = T_g - \eta_f (T_g - T_f), \qquad 0 \le \eta_f \le 1 \qquad (19)$$

The adiabatic-wall relation in Eq. (19) enforces $T_f \le T_{aw} \le T_g$.
In the current screening ROM, the film-side heat flux is written as

$$q''_{g,f} = h_{g0}(T_{aw} - T_w) \qquad (20)$$

In Eq. (20), the baseline gas-side coefficient is retained because an independently validated h_f/h_g model is unavailable. Film effectiveness is consequently an imposed boundary parameter in the ROM, rather than a prediction of detailed film-cooling behavior.

2.7. Porous effusion/transpiration mode

Film and porous-effusion modes are not applied simultaneously to the same surface element. For the porous mode, a blowing parameter is

$$B = \frac{\dot{m}'' c_{p,c}}{h_{g0}} \qquad (21)$$

The blowing parameter uses coolant heat capacity separately from the hot-gas property.
The screening blowing correction is

$$\frac{h_g(B)}{h_{g0}} = \frac{B}{e^B - 1} \qquad (22)$$

The blowing correction approaches the no-blowing limit as B → 0 and decreases monotonically with blowing.

An idealized coolant-enthalpy reference is defined as

$\dot{m}_{H,ref} = Q_{req} / [h_c(T_{lim}) - h_c(T_{in})]$ (23)

This coolant-enthalpy reference is based on the prescribed thermal load and the available coolant enthalpy rise and is used only as a screening reference.

2.8. Dimensionless screening metrics

Three dimensionless quantities are used to separate coolant-capacity, thermal-conductance, and hydraulic constraints:

$\Pi_H = \dot{m}_c [h_c(T_{lim}) - h_c(T_{in})] / Q_{req} = \dot{m}_c / \dot{m}_{H,ref}$ (24)

The enthalpy-sufficiency ratio is below unity when the available coolant enthalpy rise is insufficient for the prescribed thermal load.

$$\Pi_U = \frac{UA}{\dot{m}_c c_p} \qquad (25)$$

ΠU is an NTU-like ratio of thermal conductance to coolant heat-capacity rate.

$$\Pi_P = \frac{\Delta p}{\Delta p_{ref}} \qquad (26)$$

ΠP is retained as a relative hydraulic penalty because a validated turbine plenum-to-surface pressure budget is not available.

2.9. Baseline screening conditions

Table 1 summarizes the baseline quantities used in the ROM calculations. Values that are not established directly by experimental or literature evidence are identified as screening assumptions.

Table 1. Baseline screening conditions and assumptions.

Parameter	Value	Status
Hot-gas temperature, Tg	1700 K	nominal screening condition
Coolant inlet temperature, Tc,in	700 K	nominal screening condition
Gas-side coefficient, hg	2000 W m^-2 K^-1	screening assumption; sensitivity tested
Metal conductivity, km	22 W m^-1 K^-1	screening assumption; sensitivity tested
TBC conductivity, kTBC	1.1 W m^-1 K^-1	screening assumption; sensitivity tested
TBC thickness, tTBC	100 µm	screening assumption
Metal thickness, tm	1.0 mm	screening assumption
Mean gyroid cell size	2.5 mm nominal; 2.0–2.5 mm generic screening range	screening reference; morphology mapping uses 2.5 mm mean
Reference porosity, ε	0.50	generic dual-labyrinth screening reference; morphology match εmap ≈ 0.457
Reference Prandtl number	0.70	hot-air benchmark
Reference Reynolds number	200	common low-Re benchmark point
Initial coolant flow	0.600 g/s	reference input flow
Metal temperature limit	1300 K	screening constraint

The gas-side coefficient and the listed conductivity values are screening assumptions rather than measured blade properties; their influence is explicitly examined in the sensitivity analysis. The 0.600 g/s value is a reference input flow used for verification and regime assessment, whereas 0.768 g/s is the nominal coolant requirement obtained later from the screening calculation.

3. Verification and Evidence Controls

3.1. Exact mass and enthalpy conservation

The global mass residual is

$$R_m = \dot{m}_{in} - \dot{m}_{out} - \sum_j \dot{m}_{f,j} \qquad (27)$$

The mass residual in Eq. (27) checks that every discrete film extraction is removed from the internal coolant circuit.

The global coolant-energy residual is

$$R_E = \dot{m}_{in} h_{in} + \sum_i q_i - \dot{m}_{out} h_{out} - \sum_j \dot{m}_{f,j}\, h_{f,j} \qquad (28)$$

The energy residual in Eq. (28) checks the enthalpy balance for the remaining coolant and the extracted film stream. In the representative verification case, 0.600 g/s enters the domain and 0.150 g/s is extracted, leaving 0.450 g/s at the outlet. The residual is at numerical roundoff level, verifying the bookkeeping equations independently of the external film-cooling closure.

3.2. Analytical axial-solution verification

For constant UA, constant hot-gas temperature, and constant coolant heat capacity, the exact one-dimensional solution is

$T_{c,out} = T_g - (T_g - T_{c,in}) \exp[-UA/(\dot{m}\, c_p)]$ (29)

Using Tg = 1700 K, Tc,in = 700 K, ṁ = 0.600 g/s, cp = 1100 J kg^{-1} K^{-1}, and a verification-only UA = 0.12 W/K gives Tc,out = 866.247 K. The ROM error decreases approximately in proportion to Nx^{-1}, consistent with the first-order axial update. At Nx = 200, the outlet-temperature error is about 0.069 K (0.008%), while the associated maximum-wall-temperature difference is about 0.029 K.

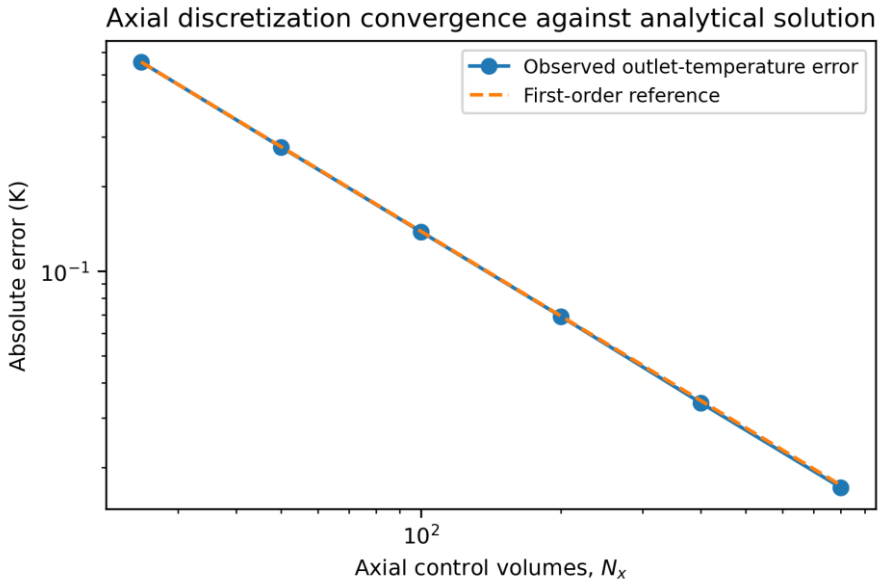


Figure 4. Axial discretization convergence against the analytical constant-UA solution. The observed slope is consistent with first-order convergence.

The same analytical model also recovers the physically required limiting behavior. As ṁ → 0, the coolant approaches the hot-gas temperature and heat removal becomes coolant-capacity limited; as ṁ → ∞, the outlet approaches the inlet temperature and total heat transfer approaches UA(Tg − Tc,in).

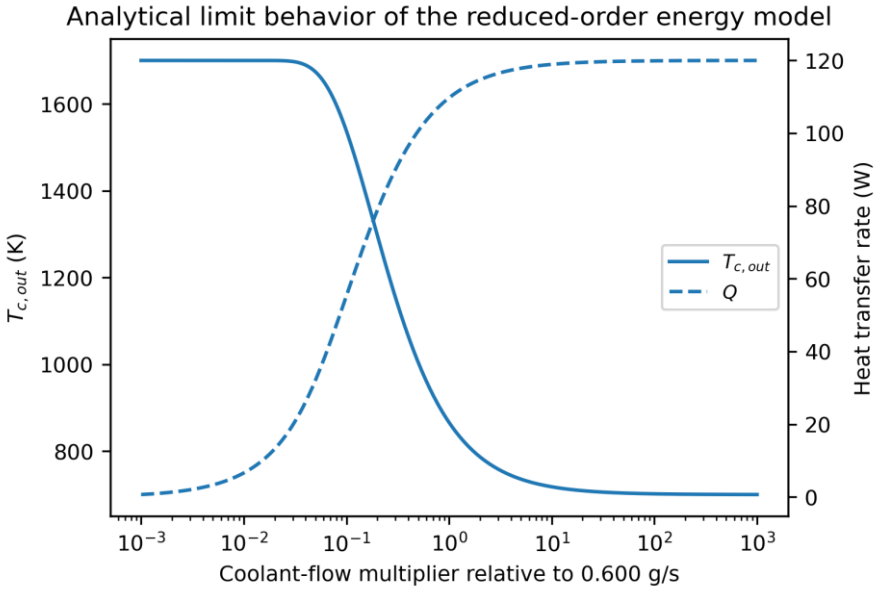


Figure 5. Analytical limiting behavior of the reduced-order energy model as coolant flow is varied over six decades.

These limits lead directly to

$$Q = \dot{m}\, c_p\, (T_g - T_{c,in})\, [1 - \exp(-\Pi_U)] \quad (30)$$

The analytical limits show that $\Pi U \ll 1$ corresponds to heat-transfer control, whereas $\Pi U \gg 1$ approaches coolant-capacity control. The transition is continuous rather than universally enthalpy-limited.

4. Results and Discussion

4.1. Literature benchmark at the reference operating point

At $Re_H = 200$ and Pr = 0.70, Eq. (14) gives $Nu_G \approx 11.35$. The Hausen straight-channel reference [30], evaluated at the same reference operating point, is approximately 6.64, so the Reynolds gyroid relation is about 1.71 times higher under the definitions adopted here. This agrees in direction with the experimental enhancement reported for gyroid TPMS relative to straight channels [9] and is used as a literature benchmark for the ROM.

The absolute Iyer gyroid correlation is not applied to the hot-air case because its Prandtl-number range differs substantially from that considered here. Retaining only its Reynolds exponent and anchoring the curve at ReH = 200, the difference from the Reynolds experimental relation is only a few percent over the common $100 \leq ReH \leq 250$ interval. The larger uncertainty is associated with transferring an absolute correlation across geometry, temperature field, wall condition, and manufactured surface rather than with the exponent difference of 0.57 versus 0.62.

Table 2. Literature-model hierarchy used by the ROM.

Source/model	Role in present study	Directly used as absolute turbine correlation?
Reynolds et al. [9]	Primary experimental sheet-gyroid Nu closure	Yes, for literature-informed screening within range
Iyer et al. [10]	Low-Re exponent and friction-factor trend	No for absolute Nu at hot-air Pr
Hausen laminar channel form [30]	Straight-channel reference only	No

Source/model	Role in present study	Directly used as absolute turbine correlation?
Brimacombe et al. [11]	Gyroid transpiration behavior benchmark	No direct coefficient transfer

4.2. Single-parameter sensitivity

A ±20% one-at-a-time analysis was used to identify the inputs with the largest influence on required coolant flow and maximum wall temperature. Gyroid cell size, the gas-side heat-transfer coefficient, and the transferred gyroid Nusselt level dominate the response. Cell size shows the clearest geometry trade-off: reducing it increases area density and shortens the hydraulic length scale, which lowers temperature, while the hydraulic penalty rises. Coolant flow is also varied in this OAT sweep as a control/design variable, but it is not treated as an independent epistemic input in the uncertainty propagation because the required coolant flow is the solved response.

Table 3. Selected ±20% screening responses for maximum metal temperature.

Variable	Low-side Tmax (K)	High-side Tmax (K)	Interpretation
Cell size aG	1295.8	1368.9	strongest geometry effect; smaller is cooler but hydraulically costly
Gas-side hg	1296.3	1365.3	strong imposed-load uncertainty
Coolant flow m-dot	1367.3	1309.4	more coolant reduces temperature but increases pressure loss
Gyroid Nu level	1365.2	1312.0	major correlation-transfer uncertainty
Film effectiveness ηf	1347.9	1323.8	moderate local effect
Porosity ε	1347.1	1326.8	moderate effect in current setup
kTBC	1328.3	1341.0	smaller effect than dominant variables
tTBC	1342.1	1329.8	smaller effect than dominant variables

The local uncertainty surrogate attributes about 91% of the response variance to the first three inputs. This result identifies the variables that should receive priority in subsequent CFD or experimental work.

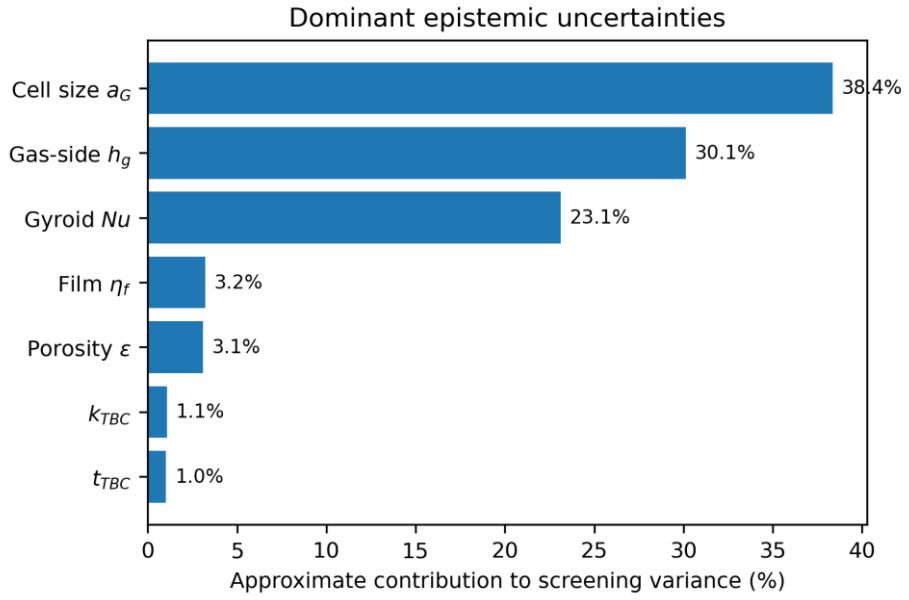


Figure 6. Approximate contribution of each epistemic input to the local coolant-requirement variance.

4.3. Epistemic uncertainty and robust screening

A local quadratic response surface was fitted through the -20%, nominal, and +20% points for each uncertain variable:

$$\dot{m}_{req} = \dot{m}_{req,0} + \sum_i \left(A_i \delta_i + B_i \delta_i^2\right) \qquad (31)$$

With seven independent uniform epistemic model inputs over ±20% and 200,000 random combinations, the solved nominal coolant requirement $\dot{m}_{req,0} = 0.768$ g/s broadens into the distribution summarized in Table 4. Coolant flow itself is not sampled as an eighth epistemic input; it is the response solved from each uncertainty realization. The 95th-percentile screening value is approximately 1.12 g/s, showing that a single nominal flow is not robust to the adopted epistemic uncertainty range.

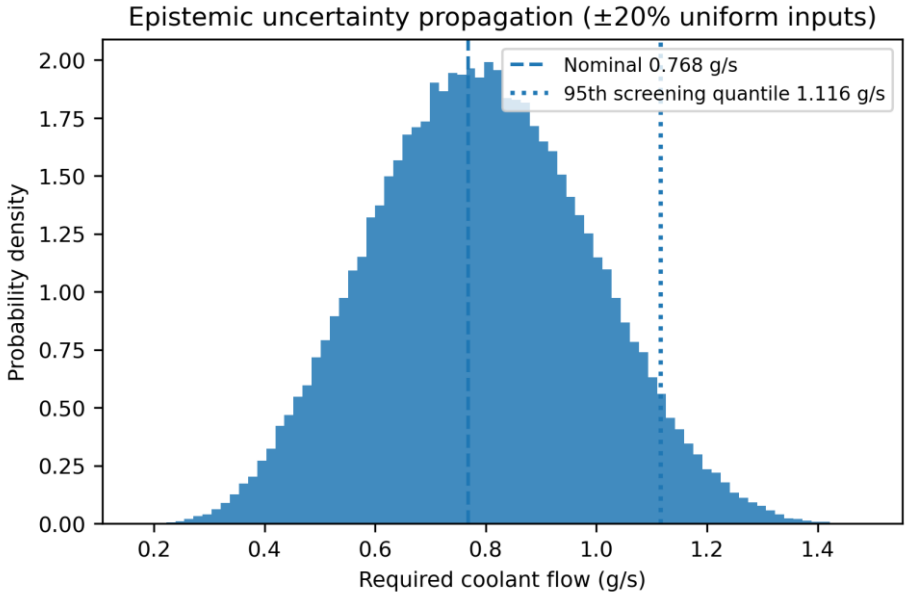


Figure 7. Distribution of the required coolant flow obtained by propagating independent ±20% epistemic uncertainties through the local ROM surrogate.

Table 4. Epistemic uncertainty summary.

Quantity	Screening result
Nominal required coolant	0.768 g/s
Mean required coolant	0.792 g/s
Median required coolant	0.789 g/s
5th percentile	0.476 g/s
95th percentile	1.116 g/s
99th percentile	1.239 g/s
Coverage at 0.768 g/s	≈46% of epistemic box
Coverage at 1.12 g/s	≈95% of epistemic box
Interpretation	screening quantiles, not engine reliability probabilities

A deterministic optimum coolant flow is therefore insufficient when the input uncertainty is appreciable.

4.4. Thermal-capacity and pressure-loss regime map

At fixed fluid properties and cross-sectional envelope, the mass flow scales as

$$\frac{\dot{m}}{\dot{m}_0} = \frac{Re_H}{Re_0}\frac{\varepsilon}{\varepsilon_0}\frac{a_{G,0}}{a_G} \qquad (32)$$

Using the nominal coolant requirement as the capacity threshold gives, for the adopted normalization,

$$Re_T = 64\frac{a_G[\mathrm{mm}]}{\varepsilon} \qquad (33)$$

The thermal-capacity boundary is relative to the adopted normalization and is not a universal transition Reynolds number.

Combining Eq. (16) with $D_h \propto a_G$ gives the approximate pressure scaling

$$\frac{\Delta p}{\Delta p_0} = \left(\frac{Re_H}{200}\right)^{1.42}\left(\frac{2}{a_G[\mathrm{mm}]}\right)^{3} \qquad (34)$$

This scaling highlights the strong hydraulic penalty associated with reducing cell size under the low-Reynolds-number pressure-loss model.

A relative pressure threshold $\Pi_P = 1$ defines the screening boundary $Re_P(a_G)$. Figure 8 shows that very small cells may leave little feasible operating range because the required coolant flow is reached only after the pressure penalty has become large. The key observation is the separation between the thermal-capacity and hydraulic boundaries rather than a unique optimum cell size.

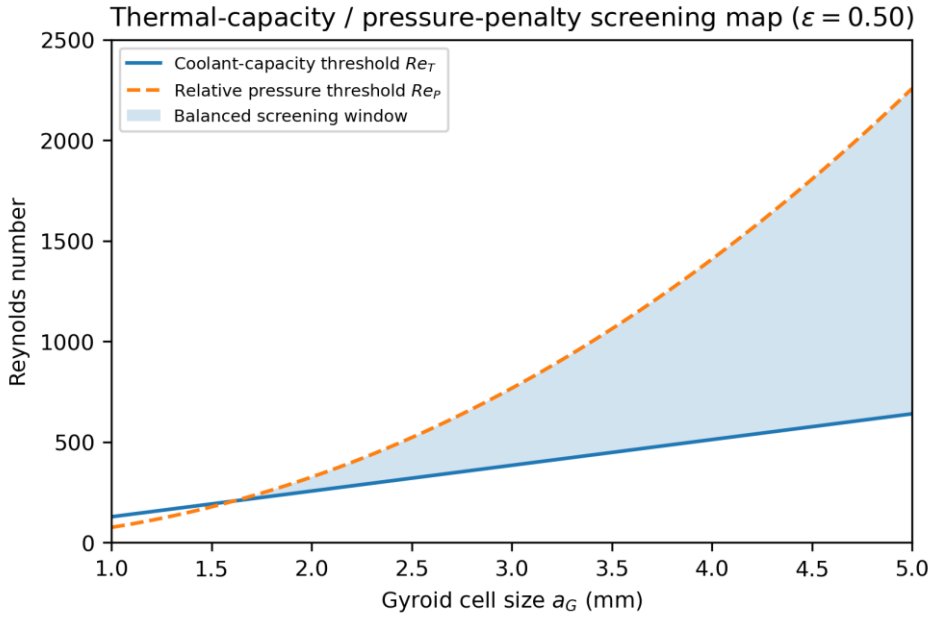


Figure 8. Thermal-capacity and pressure-penalty screening map at ε = 0.50. The shaded region denotes the relative design window under the generic screening assumptions.

4.5. Mixed heat-transfer/coolant-capacity control

The enthalpy-sufficiency ratio is evaluated from Eq. (24) as $\Pi_H = \dot{m}_c / \dot{m}_{H,ref}$, where $\dot{m}_{H,ref}$ is defined by Eq. (23) from the prescribed thermal load and available coolant enthalpy rise. The solved ROM requirement of 0.768 g/s is not the enthalpy-reference flow and is therefore not used as the denominator of Π_H. No numerical Π_H is inferred from 0.600/0.768. The strong sensitivity of required flow to the Nusselt level, together with the analytical Π_U limiting behavior, supports a mixed heat-transfer/coolant-capacity interpretation.

The screening state is therefore described as mixed heat-transfer/coolant-capacity controlled, with an additional hydraulic constraint.

4.6. Uniform versus load-matched graded surrogate

A separate mechanism test compares a uniform gyroid with a load-matched graded surrogate at nearly equal porosity and integrated internal area. The 1300 K value is used only as the temperature constraint in the separate nominal-flow screening calculation. In the grading mechanism test, 0.768 g/s is carried over only as a common reference flow and the wall temperature is allowed to emerge from the surrogate comparison; it is not forced to 1300 K. The grading rule is

$$\frac{1}{a_G(x)} = \frac{1}{a_0}[1 + \gamma\psi(x)], \qquad \left\langle \frac{1}{a_G} \right\rangle = \frac{1}{a_0} \qquad (35)$$

For γ = 0.20 and aG,0 = 2.5 mm, the controlled surrogate spans approximately 2.08–3.04 mm. At the common reference flow of 0.768 g/s, the uniform surrogate settles at 1107.2 K and the graded surrogate at 1088.5 K. The difference from the 1300 K screening constraint is expected because that constraint is not imposed in this mechanism test; 0.768 g/s is used only to place both surrogate geometries at the same flow for comparison. Using the uniform-case temperature of 1107.2 K as the matching target, the graded case requires about 0.704 g/s, corresponding to an 8.3% ROM-level reduction. The associated relative pressure measure is approximately 0.888 because the lower flow also reduces the hydraulic penalty.

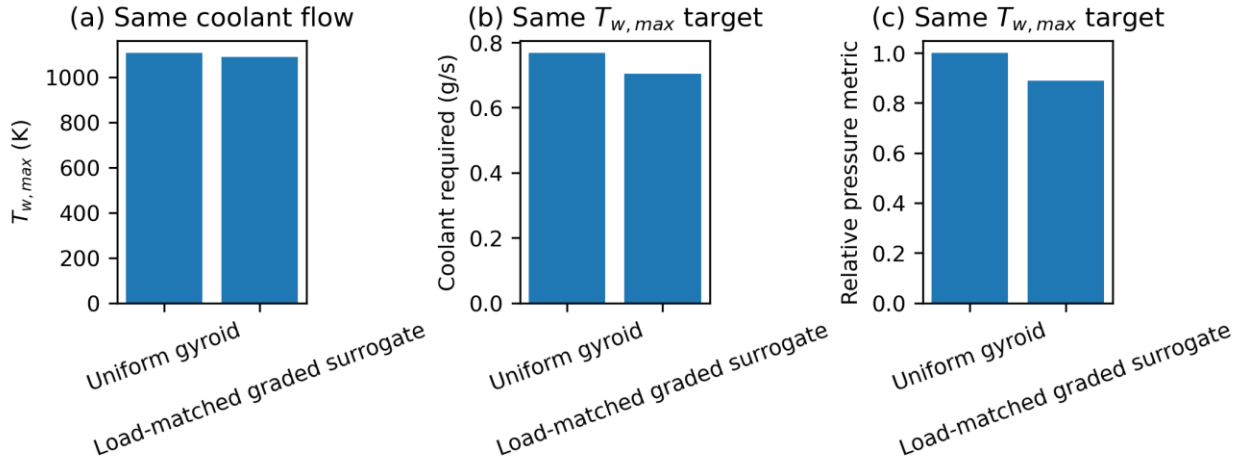


Figure 9. Comparison of the uniform and load-matched graded gyroid surrogates in the controlled ROM mechanism test.

The comparison indicates that spatial redistribution can be beneficial within the ROM, but the same gain cannot be assigned directly to the measured Gray-Scott morphology. The measured pattern varies by only about ±10% around a 2.5 mm mean cell size, whereas the controlled mechanism test uses ±20% grading. The mechanism-test result is therefore retained as a surrogate finding rather than a performance claim for the tafoni-inspired geometry.

4.7. Morphology-derived grading range and interpretation

The measured synthetic pattern shows moderate local variability. These measurements support the term tafoni-inspired morphology-derived gyroid, but they do not imply that a natural tafoni structure has been reconstructed. The mapping chain used here is

$$\text{Gray-Scott morphology} \rightarrow \{A_A, d_T, L_A\} \rightarrow \{a_G(\mathbf{x}), t_G(\mathbf{x})\} \qquad (36)$$

This mapping converts the morphology measurements into a quantitative geometry rule while retaining the limitations of the 2D-to-3D conversion.

4.8. External-cooling physical admissibility

Three mutually exclusive wall modes are enforced: internal-only, discrete-film, and porous-effusion/transpiration. This rule prevents the same external heat-flux reduction from being counted simultaneously through both T_{aw} and a transpiration blowing correction. All accepted screening states must also satisfy

$T_{c,in} \le T_c(x) \le T_w(x) \le T_{aw}(x) \le T_g$ (37)

The admissibility filter excludes states that violate the prescribed temperature ordering.

In a future pressure-coupled film model, film flow should depend on local hole geometry and pressure difference rather than being treated as an independent design variable. A low-Mach screening relation is

$$\dot{m}_f = C_d A_h \sqrt{2\rho_c(p_{pl} - p_s)} \qquad (38)$$

The low-Mach relation is used only for screening; compressibility and possible choking must be included for high-pressure turbine conditions.

5. Evidence Level, Limitations, and Scope

Table 5 distinguishes mathematical verification, literature-supported benchmarks, ROM-level mechanism tests, and hypotheses.

Table 5. Evidence and claim hierarchy of the present manuscript.

Statement	Evidence level	Allowed interpretation
Internal coolant mass/enthalpy balance closes	Mathematical/code verification	Demonstrated within ROM equations
Axial solution converges at first order	Analytical verification	Demonstrated
Gyroid Nu is higher than straight-channel reference	Literature benchmark	Supported for published sheet-gyroid range
Gyroid pressure loss can be much higher than laminar pipe flow	Literature benchmark	Supported, regime dependent
Load-matched graded surrogate reduces coolant requirement in ROM	Controlled ROM mechanism test	Supported as screening-level finding
Current Gray–Scott morphology is strongly multiscale	Morphology measurement	Not supported; variability is modest
Tafoni-inspired graded geometry has real-engine advantage	Hypothesis	CFD/experiment required
Effusion reaches a universal thermodynamic lower bound	Not supported	Use idealized coolant-enthalpy reference instead
Model predicts validated engine performance	Not supported	Use verified/literature-benchmarked ROM terminology

The main limitations arise from the screening-level boundary conditions and from transferring published gyroid heat-transfer data to a turbine context. Surface roughness, compressibility, rotation, curvature, and the higher temperature levels of an actual turbine have not been independently validated here. The morphology is a synthetic Gray-Scott pattern rather than a three-dimensional scan of natural tafoni, and the sheet-gyroid geometry has not yet been assessed for minimum printable wall thickness, stress concentration, centrifugal loading, oxidation, or TBC compatibility. The porous-effusion pressure budget is therefore reported only in relative form, and the present study contains no new CFD or experimental measurements.

Accordingly, the present results define a physics-constrained preliminary-design screening framework for subsequent CFD and experimental assessment.

6. Conclusions

The reduced-order model provides a preliminary assessment of a tafoni-inspired graded gyroid TPMS concept for turbine-blade cooling. The main conclusions are:

1. A quantitative morphology-to-gyroid mapping replaces a purely visual analogy. The selected Gray–Scott pattern is represented by void fraction, local width, and interface density, and the sheet-gyroid definition uses the mutually exclusive regions $|g| \leq tG$, $g > tG$, and $g < -tG$. The morphology-matched case uses $aG,0 = 2.5$ mm, $tG \approx 0.830$, and $\varepsilon map \approx 0.457$, with local $aG \approx 2.28$–2.78 mm.
2. Published sheet-gyroid data provide the primary internal heat-transfer benchmark. At $ReH = 200$ and $Pr = 0.70$, the Reynolds correlation gives $NuG \approx 11.35$, compared with about 6.64 for the Hausen straight-channel reference. The Iyer low-Re relation is retained for trend and pressure-loss screening rather than transferred as an absolute hot-air correlation.
3. The ROM conserves coolant mass and enthalpy, separates discrete-film and porous-effusion boundary modes, and reproduces the expected analytical limits. The axial discretization exhibits first-order convergence, with the 200-control-volume verification error below 0.01%.

4. The screening state is mixed heat-transfer/coolant-capacity controlled and is additionally constrained by hydraulic loss. The enthalpy-sufficiency metric must be referenced to $\dot{m}_{H,ref}$ from Eq. (23), not to the solved 0.768 g/s ROM requirement.
5. Epistemic uncertainty substantially broadens the coolant requirement. Cell size, gas-side heat-transfer coefficient, and the transferred gyroid Nusselt level account for most of the local response variance and should receive priority in subsequent CFD and experiments.
6. In the controlled grading mechanism test, the graded surrogate lowers the hotspot from 1107.2 K to 1088.5 K at the common 0.768 g/s reference flow and reduces the flow required to match the uniform-case 1107.2 K target from 0.768 to 0.704 g/s. This result applies to the controlled surrogate comparison and should not be assigned directly to the measured tafoni-inspired morphology.

The next stage should be a morphology-specific RVE or full conjugate CFD study to determine heat-transfer coefficients, pressure drop/permeability, and local thermal fields for the mapped gyroid. The same uniform and graded architectures can then be tested experimentally under matched coolant-flow and pressure conditions. Until such evidence is available, the ROM is best used to identify promising design regions, quantify uncertainty, and exclude physically inconsistent cooling concepts.

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RARE-EARTH-DOPED YSZ SMART OPTICAL SENSOR COATINGS FOR GAS-TURBINE AND JET-ENGINE TURBINE BLADES: A LITERATURE-BASED MULTI-CRITERIA FRAMEWORK WITH DATA-SUFFICIENCY SCREENING FOR TEMPERATURE AND STRUCTURAL HEALTH MONITORING

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Abstract
The primary function of thermal barrier coatings (TBCs) used in the hot sections of gas turbines and aviation jet engines is to protect metallic turbine blades from high temperatures. In next-generation engines, however, thermal insulation alone is not sufficient; non-contact monitoring of coating temperature, thermal history, and, where possible, damage indicators such as stress, deformation, cracking, and delamination is also desirable. Yttria-stabilized zirconia (YSZ) doped with rare-earth ions is attractive for this purpose because it can combine the well-established thermal-barrier behavior of YSZ with the photoluminescence properties of rare-earth ions within the same material family. In this study, six optically active ions—Tm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, Eu^{3+}, and Dy^{3+}—were evaluated as alternative or architecture-dependent sensor activators for YSZ rather than as a mixture to be incorporated simultaneously into a single coating.
The aim of this study is to evaluate the available experimental evidence for Tm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, Eu^{3+}, and Dy^{3+} within a common data structure, identify missing data, and establish a MATLAB framework to guide subsequent experiments. Concentration-dependent photoluminescence intensity I(c), fluorescence intensity ratio FIR(T), fluorescence lifetime τ(T), and thermal conductivity k(c,T) were treated as the principal data groups. The literature reports photoluminescence peak concentrations of approximately 0.50 mol% for Tm^{3+}, approximately 0.50–0.75 mol% for Ho^{3+} depending on the study, and approximately 0.75 mol% for Nd^{3+}. Er^{3+} provides strong evidence for high-temperature thermal-history sensing, while coating-scale thermometry studies are available for Eu^{3+} and Dy^{3+}; experimental studies on stress and delamination monitoring are also available for Eu^{3+}- and Er^{3+}-based systems.
Absolute photoluminescence intensities were not compared directly because the host phase, processing method, excitation power, optical collection geometry, and specimen configuration differ among studies. For Tm^{3+}, the distinct PL peak at approximately 0.50 mol% and the blue emission near 458 nm provide a practical starting point for subsequent concentration scans. Curve fitting of six digitized Ho^{3+} data points from Yang et al. [7] yielded c_{peak} = 0.475 mol%, R^2 = 0.874, and RMSE = 0.068. Because high-temperature optical calibration, low-dopant k(c,T) data, and SHM calibration are not available together for the same candidate under comparable coating conditions, multi-criteria ranking and PSO were not applied.
At this stage, the study defines an experimental roadmap for generating comparable data rather than producing a material ranking. The main requirements are high-temperature FIR(T)/τ(T) calibration, photoluminescence–stress calibration, controlled crack/delamination imaging, thermal-cycling durability, and k(c,T) measurements. Once these data sets are completed, the multi-criteria QPI and PSO approach can be used to support material, concentration, and coating-architecture selection.
Keywords: thermal barrier coating; YSZ; rare-earth doping; photoluminescence; optical thermometry; structural health monitoring

Highlights
- Six rare-earth ions were compared as separate candidate systems for YSZ-based optical sensor coatings.
- The PL peak near 0.50 mol% for Tm^{3+} provides a practical starting point for subsequent comparative experiments.
- Er^{3+} provides strong evidence for high-temperature thermal-history sensing; direct experimental evidence exists for stress and delamination monitoring with Eu^{3+}, and related evidence for delamination monitoring with Er^{3+}/Yb^{3+}- and Er^{3+}-based systems.
- The Ho^{3+} curve-fitting test yielded c_{peak} = 0.475 mol%, R^2 = 0.874, and RMSE = 0.068.

- The current data set is insufficient for full QPI/PSO comparison; the missing data groups should be completed through targeted experiments.

1. Introduction

Gas turbines and jet engines operate at increasingly high turbine inlet temperatures to achieve higher efficiency. Under these conditions, direct exposure of nickel-based superalloy turbine blades to hot gases would impose unacceptable thermal loads and oxidation. Ceramic thermal barrier coatings are therefore used on hot-section components such as turbine blades, vanes, and combustion chambers. YSZ-based TBCs have long been a key industrial solution because of their low thermal conductivity, compatible thermal expansion, and mature coating technologies [1]. At operating temperatures above 1200 °C, however, phase transformation, sintering, thermal radiation, interfacial stresses, thermally grown oxide (TGO) formation, and crack/delamination growth can limit coating life [1,2,13].

The central approach of this study is to add optical interrogation capability to the thermal-protection function of the TBC. A coating containing an appropriate amount of optically active rare-earth ions can be excited by a laser or another light source at a suitable wavelength; the intensity, spectral ratio, or decay lifetime of the emitted photoluminescence signal can then be measured remotely. This enables temperature and thermal-history information to be obtained without embedding wires or conventional contact sensors in the coating [3,4,14–16].

A further objective is to enable structural health monitoring (SHM) through the coating. Stress, strain, microcracking, delamination, or partial separation within the coating can alter the photoluminescence peak position, linewidth, intensity, or the optical reflection/scattering path. Experimental studies have shown that residual-stress distributions and their evolution during thermal cycling can be measured in Eu^{3+}-doped YSZ coatings by photoluminescence piezospectroscopy; delamination can be detected with high contrast using YSZ:Eu luminescent sublayers; and subcritical delamination-crack growth can be monitored by luminescence imaging in Er^{3+}/Yb^{3+}-doped YSZ [17–20]. Rare-earth-doped YSZ sensor coatings have also been reported to exhibit high-temperature strain/stress behavior close to that of conventional YSZ [21]. These studies show that the smart-TBC concept is supported by experimental evidence rather than being solely a theoretical proposal.

A critical scientific distinction is nevertheless required. Strong photoluminescence from a given ion does not necessarily mean that the same ion is also the best high-temperature thermometer, stress sensor, or crack indicator. Likewise, the dopant concentration that gives the highest room-temperature luminescence intensity may not provide the highest thermometric sensitivity or the lowest thermal conductivity in the 1200–1500 K range. Processing route, Y_2O_3 content, crystal phase, porosity, grain structure, excitation wavelength, optical collection geometry, and coating thickness can substantially affect the results [2,3,13]. This variability makes it unreliable to select a single “best ion” directly from absolute luminescence intensities reported in different studies.

This study evaluates concentration–photoluminescence data for Tm^{3+}, Ho^{3+}, and Nd^{3+}; high-temperature thermal-history data for Er^{3+}; and coating-scale thermometry evidence for Eu^{3+} and Dy^{3+}. The six ions are treated as separate sensor candidates rather than as a formulation to be added simultaneously to one coating. Specific multilayer or multi-activator architectures may be investigated separately in future work.

The main contributions of the study are the separation of different experimental data types within a common record structure, withholding multi-criteria ranking when data are incomplete, demonstration of curve fitting and peak-position reproduction using Ho^{3+} data, and inclusion of stress/damage-monitoring requirements in the experimental roadmap in addition to temperature sensing.

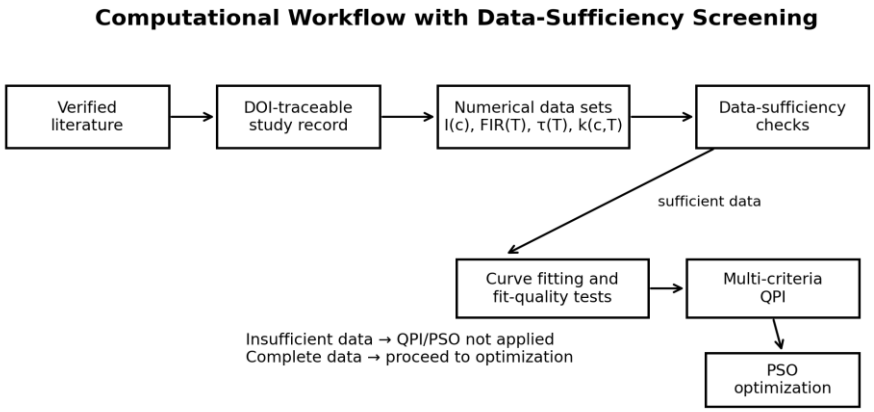


Figure 1. Computational workflow with data-sufficiency screening. The QPI/PSO stage is not entered until the required experimental data groups are available.

2. Literature-Based Experimental Evidence

2.1. Literature search and evidence selection

Candidate studies were identified in Web of Science, Scopus, ScienceDirect, SpringerLink, and Google Scholar using combinations of the keywords YSZ, stabilized zirconia, Tm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, Eu^{3+}, Dy^{3+}, photoluminescence, fluorescence intensity ratio, lifetime thermometry, thermal-history sensor, thermal barrier coating, thermal conductivity, photoluminescence piezospectroscopy, stress, and delamination. Studies were entered into the data record if they used YSZ or a closely related stabilized-zirconia host, provided at least one quantitative data set or experimental reference point, and were bibliographically verifiable.

The search was not designed as a complete PRISMA-type systematic review, but as a source-verified data-selection process for the computational framework. PL peak values, high-temperature results, and measurement modes from different studies were not merged into a single material curve; each study was retained separately with its host phase, processing route, concentration range, excitation–emission conditions, and measurement mode.

2.2. Tm^{3+}-doped YSZ

Xu et al. produced cubic YSZ single crystals containing 0.2–3.0 mol% Tm_2O_3 by the optical floating-zone method [5]. Under 356 nm excitation, strong blue emission near 458 nm and weaker emission bands at longer wavelengths were reported. Luminescence intensity increased at low Tm_2O_3 concentrations, reached a maximum at approximately 0.50 mol%, and then decreased at higher dopant levels because of concentration quenching.

The approximately 0.50 mol% peak reported by Xu et al. [5] is an experimental PL maximum for Tm^{3+} and provides a reference value for subsequent concentration scans. It is not interpreted here as an optimum for high-temperature thermometry, stress measurement, or crack detection.

2.3. Ho^{3+}-doped YSZ

Tan et al. reported strong emission near 553.5 nm under 448 nm excitation in Ho^{3+}-doped YSZ single crystals [6]. Ho_2O_3 contents of 0.20, 0.50, 0.75, 1.00, 1.50, and 2.00 mol% were evaluated, and the strongest fluorescence was observed at approximately 0.75 mol%.

Yang et al. investigated 0–1.20 mol% Ho_2O_3 in a related Y_2O_3-stabilized ZrO_2 system, reported emission bands near 540, 551, 670, and 757 nm under 446 nm excitation, and found maximum luminescence at approximately 0.50 mol% [7]. The quenching observed at higher concentrations was attributed to electric dipole–dipole interactions.

The different Ho^{3+} peak concentrations reported in the two studies, 0.75 and 0.50 mol%, show that the optimum dopant level does not depend on ion identity alone. Because the host phase, Y_2O_3 content, crystal phase, processing method, and measurement protocol differ, these results were retained as separate experimental reference values.

2.4. Nd^{3+}-doped YSZ

Zhang et al. produced YSZ single crystals containing 0.30–1.50 mol% Nd_2O_3 by the optical floating-zone method and evaluated both up-conversion luminescence and Judd–Ofelt analysis [8]. The maximum emission intensity reported near 0.75 mol% Nd_2O_3 was retained in the record as the reference peak value, while excitation/emission conditions and the concentration-quenching mechanism were stored as study metadata.

As with Tm^{3+} and Ho^{3+}, the 0.75 mol% value for Nd^{3+} is only the photoluminescence optimum under the specific experimental conditions of the source study. Real-time temperature or damage monitoring on a turbine blade requires high-temperature calibration for the intended measurement mode.

2.5. Er^{3+}-doped YSZ

Among the six selected candidates, Er^{3+} has the strongest direct evidence for high-temperature thermal-history sensing. Copin et al. prepared a YSZ system containing 8.3 mol% $YO_{1.5}$ and 1.5 mol% $ErO_{1.5}$ (0.75 mol% Er_2O_3-equivalent) by a sol–gel route and applied 15 min isothermal exposures between 1173 and 1423 K [9]. Permanent changes in emission intensity and fluorescence lifetime were used to estimate the temperature to which the specimen had previously been exposed. This was not instantaneous/in-situ thermometry, and the 1.5 mol% Er composition was not presented as a concentration optimum.

Amiel et al. compared intensity-ratio and lifetime-based methods in a YSZ:Er^{3+}/YSZ:Eu^{3+} fluorescent thermal-history sensor and reported good thermal sensitivity over 1223–1423 K [10]. Er^{3+} records were therefore retained separately as thermal-history-sensing data.

Er^{3+} is also relevant to delamination detection. Eldridge and Wolfe monitored subcritical delamination-crack growth in Er^{3+}/Yb^{3+}-doped YSZ by up-conversion luminescence imaging [18]. Fouliard et al. modeled and experimentally quantified delamination contrast in TBC configurations containing an Er^{3+}-doped YSZ luminescent layer [19]. These studies support delamination monitoring within the Er^{3+} family; their compositions and measurement modes were not combined with the thermal-history data into a single numerical curve.

2.6. Eu^{3+}-doped YSZ

For Eu^{3+}, direct YSZ:Eu evidence was evaluated separately from evidence obtained using a different-host phosphor beneath a YSZ top coat. Feist and Heyes showed that the emission decay lifetime of YSZ:Eu is temperature dependent over approximately 299–1073 K (26–800 °C) and that the 591 and 607 nm emission lines can be used for thermometry [14]. Yang et al. demonstrated direct YSZ:Eu sensor-TBC operation over approximately 400–800 °C [11]. Abou Nada et al. used a Y_2O_3:Eu luminescent layer beneath an APS YSZ top coat to perform remote temperature measurement through the YSZ [3]. Because Y_2O_3:Eu is not the same host as YSZ:Eu, this study was retained as related coating-scale optical-access evidence and was not included directly in the YSZ:Eu temperature-window calculation.

A second important role of Eu^{3+} in this study is the evidence for stress and damage sensing. Eldridge et al. experimentally demonstrated a self-indicating coating concept using a YSZ:Eu luminescent sublayer, observing a pronounced emission increase in TBC delamination regions [17]. Zhao et al. used the relationship between the peak position of the $^5D_0 \rightarrow {}^7F_2$ transition and stress in an 8YSZ:Eu coating to monitor residual-stress distribution and its evolution during thermal cycling at 1300 °C by photoluminescence piezospectroscopy [20]. These studies provide positive experimental evidence that the coating can act as a sensor of mechanical condition as well as temperature.

The selected direct YSZ:Eu in-situ thermometry evidence nevertheless has an upper limit of approximately 1073 K, below the 1200–1500 K engineering window. Thus, although Eu^{3+} is a strong SHM reference, additional high-temperature validation is required for thermometry in the turbine-relevant window.

2.7. Dy^{3+}-doped YSZ

Dy^{3+}-doped YSZ is an important high-temperature reference for intensity-ratio and lifetime-based thermometry. Abou Nada et al. evaluated 10 wt.% DySZ as a temperature sensor over approximately 400–1000 °C, while Yang et al. demonstrated temperature sensing in APS YSZ:Dy sensor coatings over approximately 500–900 °C and through top coats up to 300 µm thick [3,11]. Heyes et al. established the basic principles of two-color phosphor thermometry for surface-temperature measurement [16].

Because Dy_2O_3 at high loadings can also contribute to the thermal-barrier composition of YSZ, Dy^{3+} occupies a distinctive position in considering sensing and thermal-barrier functions together. However, the data set used here does not provide a low-concentration PL-peak optimization for Dy^{3+}.

2.8. Literature basis for stress, crack, and delamination monitoring with rare-earth-doped YSZ

The smart-TBC concept should not be reduced to temperature measurement alone. TBC damage commonly develops through thermal-expansion mismatch, TGO growth, sintering, phase transformation, and local stress concentrations. These processes promote microcrack growth, interfacial delamination, and eventual top-coat spallation [1]. A truly smart coating would therefore benefit from providing an indicator of mechanical integrity in addition to temperature information.

In photoluminescence piezospectroscopy, the peak wavelength or wavenumber of an optical transition changes with stress because of crystal-field and elastic-strain effects. Once calibrated, the emission-peak shift can serve as a stress indicator. The fact that residual-stress distribution and its evolution during thermal cycling have been measured in Eu^{3+}-doped 8YSZ using this approach [20] shows that optically active ions in YSZ can carry mechanical information.

The mechanism can differ for crack and delamination detection. A crack or separated interface can alter the reflection/scattering paths of excitation and emission light and produce high contrast in luminescence intensity. Demonstration of delamination using YSZ:Eu sublayers [17], monitoring of early-stage subcritical delamination-crack growth in Er^{3+}/Yb^{3+}-doped YSZ by up-conversion luminescence imaging [18], and experimental/model-based quantification of delamination contrast in Er^{3+}-based layers [19] support the applicability of this mechanism.

Existing studies show that stress and delamination can be monitored by optical methods [17–20]. The evidence is not equally distributed among the candidates: strong direct evidence for stress and delamination is available for Eu^{3+}, while related/partial evidence for delamination is available for the Er^{3+} family. Comparable SHM calibrations for Tm^{3+}, Ho^{3+}, Nd^{3+}, and Dy^{3+} are not available in the selected source set.

2.9. Rationale for prioritizing Tm^{3+} in experimental work

For Tm^{3+}, a distinct PL maximum near 0.50 mol%, blue emission near 458 nm under 356 nm excitation, and a broad tested concentration range of 0.2–3.0 mol% have been reported [5]. Once the full ordinates are digitized, this broad concentration range will allow the concentration-quenching curve to be modeled.

These features justify prioritizing Tm^{3+} in comparative experiments performed under identical conditions [5]. However, because the Ho^{3+} and Nd^{3+} studies used different excitation powers, optical collection systems, specimen thicknesses, and crystal structures, the absolute brightness of the candidates cannot be compared directly across the existing studies.

RE_2O_3-equivalent mol% was adopted as the common notation for concentration comparisons. Values reported directly as RE_2O_3 for Tm, Ho, and Nd were retained unchanged; 1.5 mol% $ErO_{1.5}$ was converted stoichiometrically to 0.75 mol% Er_2O_3-equivalent. No reliable PL-peak mol% conversion was performed for Dy data reported in wt.% or host-composition form, and these values were not compared on the same numerical axis.

Table 1. Main literature reference data included in the MATLAB record structure.

Ion / key source	Concentration / PL evidence	High-temperature evidence	SHM / damage evidence	Role in this study
Tm^{3+} [5]	0.2–3.0 mol% Tm_2O_3; PL peak ~0.50 mol%; 356/458 nm	Sensor calibration missing in the turbine window	No direct evidence in the selected set	PL / quenching reference
Ho^{3+} [6,7]	Ho_2O_3; two separate studies; PL peaks ~0.75 and ~0.50 mol%	Thermometry calibration missing in the turbine window	No direct evidence in the selected set	Key example of study-dependent PL peak

Ion / key source	Concentration / PL evidence	High-temperature evidence	SHM / damage evidence	Role in this study
Nd^{3+} [8]	0.30–1.50 mol% Nd_2O_3; PL peak ~0.75 mol%	Thermometry calibration missing in the turbine window	No direct evidence in the selected set	PL / Judd–Ofelt / quenching reference
Er^{3+} [9,10,18,19]	1.5 mol% $ErO_{1.5}$ = 0.75 mol% Er_2O_3-equivalent; not an optimum	1173–1423 K and 1223–1423 K thermal-history sensing	Related/partial delamination evidence [18,19]	High-T thermal history + delamination monitoring
Eu^{3+} [3,11,14,17,20]	Fixed compositions; YSZ:Eu and related Y_2O_3:Eu/YSZ evidence kept separate; no PL optimum	Direct YSZ:Eu: 299–1073 K; Y_2O_3:Eu/YSZ [3] retained as related optical-access evidence	Strong direct evidence for stress + delamination [17,20]	Thermometry + SHM reference
Dy^{3+} [3,11,16]	Fixed sensor/host compositions; some sources use wt.%; no common mol% PL-peak value	Approximately 673–1273 K; in-situ thermometry	No direct SHM calibration in the selected set	High-T in-situ thermometry reference

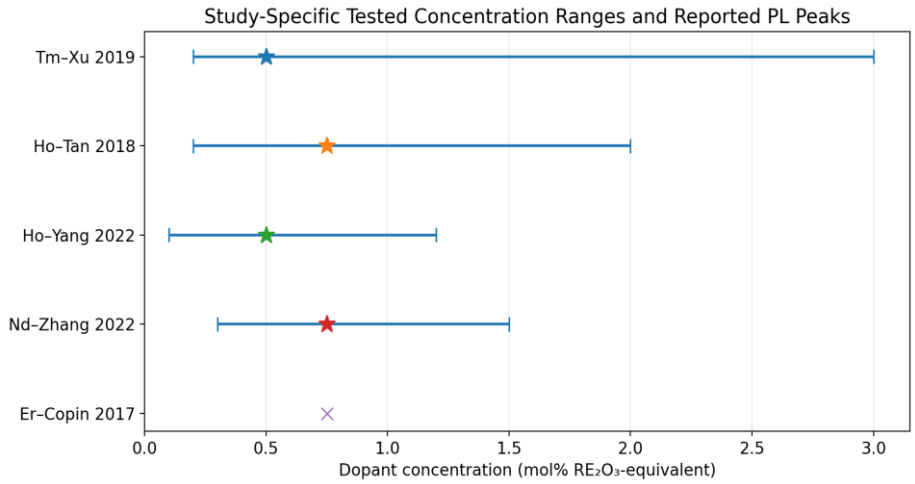


Figure 2. Tested dopant concentration ranges and reported photoluminescence peak positions for the selected studies, shown on an RE_2O_3-equivalent mol% basis. The Er^{3+} entry, 1.5 mol% $ErO_{1.5}$ = 0.75 mol% Er_2O_3-equivalent, is a fixed-composition high-temperature study and not a concentration optimum.

3. Computational Method

3.1. DOI-traceable records and data classes

Each experimental study is stored as an independent record in the MATLAB framework. The record includes study identity, ion, DOI, host phase, synthesis/coating method, concentration range, PL peak value, excitation/emission wavelengths, valid temperature range, measurement mode, and, where available, the concentration-quenching mechanism. This structure prevents data from different processes from being combined inadvertently into a single "virtual material."

The computational framework uses four main quantitative data groups: (i) concentration-dependent luminescence intensity I(c), (ii) fluorescence intensity ratio FIR(T), (iii) fluorescence lifetime τ(T), and (iv) thermal conductivity k(c,T). Temperature-sensing modes are also separated into "in-situ

thermometry" and "thermal-history sensing." A thermal-history data set is not assumed to provide the FIR(T) or τ(T) calibration required for in-situ thermometry.
Two additional data groups were defined for SHM assessment: (v) stress/strain-dependent optical peak shift or piezospectroscopic sensitivity and (vi) crack/delamination luminescence contrast. They were not included in the current QPI/PSO calculation because sufficiently complete and comparable data are not available for the six candidates.

3.2. Data-sufficiency check

The reference data-sufficiency criterion requires at least four I(c) points, at least four FIR(T) or τ(T) points compatible with the target measurement mode, and at least six k(c,T) points. Thermal-conductivity data are also expected to cover at least two temperatures and three concentration levels, while the measurement mode must be compatible with the intended application:

$$G = (N_I \geq 4) \wedge [(N_{FIR} \geq 4) \vee (N_\tau \geq 4)] \wedge (N_k \geq 6) \wedge (N_{T,k} \geq 2) \wedge (N_{c,k} \geq 3) \wedge (M_{mode} = 1) \quad (1)$$

These thresholds are not physical constants; they are data-sufficiency criteria intended to make curve fitting and candidate comparison minimally identifiable under sparse-literature conditions. Threshold sensitivity was examined using relaxed (3/3/3/4), reference (4/4/4/6), and strict (5/5/5/9) scenarios.
The engineering temperature window for the turbine application was defined as T_{gate} = 1200–1500 K. The fraction of a source range overlapping this window is expressed as $C_T = 100 \cdot \Delta T_{overlap}/300$. C_T quantifies only temperature-range overlap and does not make different measurement modes equivalent.

3.3. Optical response models

For two thermally coupled luminescence levels, the fluorescence intensity ratio can be written in Boltzmann form:

$$FIR(T) = B \cdot \exp[-C_2 \Delta E/T], \quad C_2 = hc/k_B = 1.438776877\ K \cdot cm \quad (2)$$

The corresponding relative temperature sensitivity is:

$$S_r(T) = (100/FIR) \cdot (dFIR/dT) = 100 \cdot C_2 \Delta E/T^2 \quad [\% \cdot K^{-1}] \quad (3)$$

A positive, single-peaked surrogate model was used to represent concentration quenching:

$$I(c) = A \cdot c \cdot \exp[-(c/c_q)^m] \quad (4)$$

Here, c is the dopant concentration, c_q is the characteristic concentration scale, m is the exponent controlling the post-peak decay, and A is the amplitude parameter. The analytical peak position is obtained from $c_{peak} = c_q \cdot m^{(-1/m)}$. The fitted peak is compared with the reference PL peak reported in the same source.

3.4. Thermal surrogate model and multi-criteria quality-performance index

When sufficient k(c,T) and optical data are available, MATLAB fits a low-order concentration–temperature surrogate model. Model parameters are required to be derived from source-verified experimental data rather than assumed constants.
For a future data-complete stage, the basic multi-criteria quality-performance index (QPI) combines normalized temperature sensitivity for the target measurement mode, luminescence intensity, lifetime, the contribution of low thermal conductivity, and evidence quality:

$$QPI = w_1 S_T^* + w_2 I^* + w_3 \tau^* + w_4 (1 - k^*) + w_5 E \quad (5)$$

For Eq. (5), nominal weights were defined as $w_1 = 0.25$, $w_2 = 0.30$, $w_3 = 0.15$, $w_4 = 0.20$, and $w_5 = 0.10$. Because the data-sufficiency criteria are not satisfied, these weights do not produce a material ranking in the present study. Weight sensitivity and ranking stability should be tested at the data-complete stage.
A robustness score that penalizes uncertainty is defined as:

$$R(c) = (1/N_T) \cdot \Sigma_i\ QPI(c,T_i) - \lambda \cdot \sigma_{QPI}(c) \quad (6)$$

In the present study, λ is not an active physical parameter; it should be evaluated by sensitivity analysis at the data-complete stage.

3.5. Particle swarm optimization

For concentration optimization, the classical PSO update follows the approach of Kennedy and Eberhart [12]:

$$v_i(t+1) = \omega v_i(t) + c_1 r_1[p_i - x_i(t)] + c_2 r_2[g - x_i(t)], \quad x_i(t+1) = x_i(t) + v_i(t+1) \tag{7}$$

In the current MATLAB implementation, 50 particles and 150 iterations were defined, with $\omega = 0.90 \rightarrow 0.35$, $c_1 = 1.70$, $c_2 = 1.90$, and a maximum particle velocity equal to 18% of the allowed concentration range. Because the system-level data-sufficiency gate was not passed, these settings do not affect the physical results reported here.

3.6. Proposed extended metrics for structural health monitoring

One of the most direct optical quantities for stress sensing is the sensitivity of the emission-peak position to stress. The piezospectroscopic sensitivity that should be calibrated in future for the same ion and coating can be expressed as:

$$S_\sigma = \partial\lambda_p/\partial\sigma \tag{8}$$

where λ_p is the selected emission-peak wavelength and σ is the mechanical/thermal stress. To generate a stress map, the effect of temperature on the spectral peak must be separated from the stress contribution.

For cracks or delamination, the optical contrast can, for example, be defined as:

$$C_d = (I_d - I_0)/I_0 \tag{9}$$

where I_d is the luminescence intensity in the damaged region and I_0 is the intensity in the intact reference region. This metric depends on delamination geometry, sensing-layer depth, scattering, porosity, and optical collection geometry; experimental calibration is therefore required for each coating architecture [17–19].

When sufficient data are available, the extended quality index including structural health monitoring can be written as:

$$QPI_{SHM} = w_1 S_T^* + w_2 I^* + w_3 \tau^* + w_4(1 - k^*) + w_5 S_\sigma^* + w_6 C_d^* + w_7 E \tag{10}$$

Equation (10) was not used in this study to generate a material ranking. The weights w_1–w_7 are to be redefined in future for the extended SHM index; the nominal five-weight set in Eq. (5) was not transferred directly to Eq. (10). The purpose is to define explicitly which measurable quantities must be obtained from future experiments.

Table 2. Data-sufficiency threshold sensitivity and nominal QPI/PSO settings. QPI and PSO are inactive in the present results.

Category	Parameter	Value
Threshold sensitivity	Relaxed N_I / N_{FIR} / N_τ / N_k	3 / 3 / 3 / 4
Threshold sensitivity	Reference N_I / N_{FIR} / N_τ / N_k	4 / 4 / 4 / 6
Threshold sensitivity	Strict N_I / N_{FIR} / N_τ / N_k	5 / 5 / 5 / 9
Threshold sensitivity	Min. T × c (relaxed / ref. / strict)	2×2 / 2×3 / 3×3
Data-sufficiency check	Current system outcome	PSO not applied in any of the three scenarios
QPI	Nominal weights (inactive)	0.25 / 0.30 / 0.15 / 0.20 / 0.10
PSO	Particles / iterations	50 / 150
PSO	Inertia weight	0.90 → 0.35
PSO	c_1 / c_2	1.70 / 1.90
PSO	v_{max}	0.18 × search range

4. Results

4.1. Study-specific concentration evidence

The verified record shows that the PL peak concentration is not a universal material constant independent of experimental conditions. Peak values of approximately 0.50 mol% for Tm^{3+} [5], 0.75 mol% [6] and 0.50 mol% [7] for Ho^{3+}, and approximately 0.75 mol% for Nd^{3+} [8] have been reported. Because a fixed composition was used in the high-temperature Er^{3+} studies, the 1.5 mol% Er value was not interpreted as an "optimum" [9,10].

The reported peak concentrations for Tm^{3+}, Ho^{3+}, and Nd^{3+} fall within a similar low-mol% range; however, they were obtained using different host phases, excitation conditions, and optical setups. In addition, the Nd^{3+} data are based on up-conversion luminescence, whereas the Tm^{3+} and Ho^{3+} values originate from different photoluminescence measurement conditions. These differences were taken into account by treating the peak concentrations as source-specific reference values.

4.2. Spectral behavior and concentration quenching

Tm^{3+} produces blue emission near 458 nm, while Ho^{3+} produces strong green emission near 551–553.5 nm [5–7]. The Nd^{3+} study includes up-conversion luminescence and Judd–Ofelt analysis [8]. Different spectral regions impose different requirements on the laser/LED source, optical filters, and detector. System design should therefore consider the applicability of the optical hardware in the turbine environment as well as the material itself.

Concentration quenching is a physical design constraint. As dopant content increases, the signal initially strengthens because the number of optically active centers increases; beyond a certain level, however, energy transfer and ion–ion interactions increase non-radiative losses and reduce luminescence. Accordingly, the assumption that "more rare earth = a better sensor" is not valid. A separate I(c) curve is required for each ion.

4.3. High-temperature evidence and turbine relevance

The selected Er^{3+} thermal-history data have been demonstrated over 1173–1423 K [9] and 1223–1423 K [10], providing substantial overlap with the 1200–1500 K engineering window. The selected upper limit of the direct YSZ:Eu in-situ thermometry evidence is approximately 1073 K [11,14], whereas for Dy^{3+} it is approximately 1273 K [3,11,16]. Because the Y_2O_3:Eu/YSZ system of Abou Nada et al. [3] uses a different host architecture, it was not included in the Eu^{3+} C_T calculation and was retained separately as related coating-scale optical-access evidence.

When only temperature-range overlap with the 1200–1500 K window is considered, Er^{3+} provides approximately 74% coverage in thermal-history mode and Dy^{3+} approximately 24% in in-situ mode. The selected Eu^{3+} in-situ evidence lies below this window. These percentages are not a material ranking of the form "Er is better than Dy"; they quantify only the valid temperature ranges of different measurement modes.

4.4. Numerical preparation and Ho^{3+} curve-fitting test

Six concentration–intensity points from the Ho^{3+} series of Yang et al. [7] were digitized from the published graph and used with Eq. (4) for curve fitting and peak-position reproduction. Full ordinate digitization has not yet been completed for Tm^{3+} and Nd^{3+}, so the same test was not applied to those two candidates.

4.4.1. Curve-fitting test for Yang et al. Ho^{3+} data

The highest emission-peak values in the 530–565 nm green band were approximately digitized from Figure 10 of Yang et al. [7] for Ho_2O_3 concentrations of 0.10, 0.30, 0.50, 0.75, 1.00, and 1.20 mol%. After normalizing the 0.50 mol% sample to $I/I_{max} = 1$, the resulting values were 0.470, 0.707, 1.000, 0.765, 0.586, and 0.441, respectively.

Nonlinear least-squares fitting of Eq. (4) to these six points yielded A = 4.595, c_q = 0.533 mol%, and m = 1.139. The global fit gave R^2 = 0.874 and RMSE = 0.068. The analytical peak was c_{peak} = 0.475 mol%; relative to the literature peak of 0.50 mol%, the absolute peak error was 0.025 mol% and the relative error, at the displayed precision, was approximately 5.0%.

Table 3. Ho^{3+} concentration–PL data approximately digitized from Figure 10 of Yang et al. [7] and the Eq. (4) fit.

Ho_2O_3 (mol%)	Digitized I/I_{max}	Eq. (4)	Residual (measurement − model)
0.10	0.470	0.396	+0.074
0.30	0.707	0.819	−0.113
0.50	1.000	0.906	+0.094
0.75	0.765	0.787	−0.022
1.00	0.586	0.592	−0.006
1.20	0.441	0.443	−0.002

When the Dexter transformation reported by Yang et al. was repeated for the high-concentration points, the regression slope was approximately −1.906, in good agreement with the source value of approximately −1.95. This independent check indicates that the graph digitization preserves the high-concentration quenching trend with reasonable accuracy.

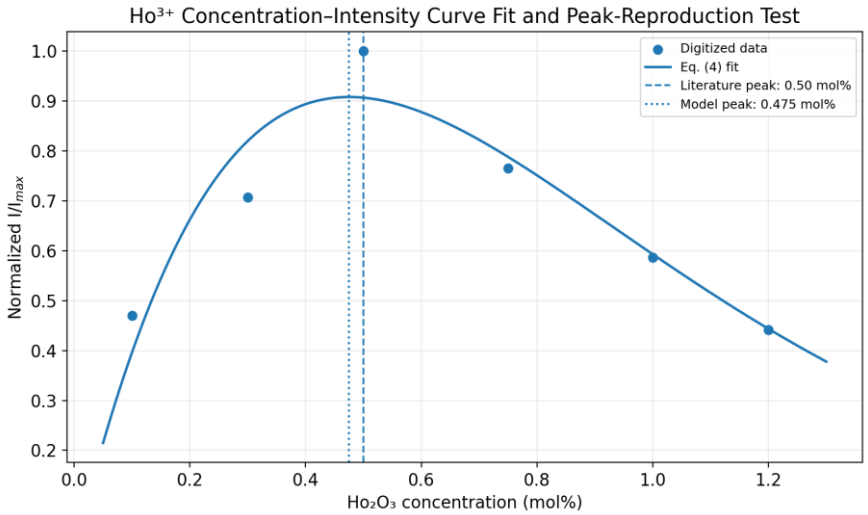


Figure 3. Curve-fitting and peak-position reproduction test for the Ho^{3+} concentration–luminescence data using Eq. (4). The model reproduces the literature peak of 0.50 mol% at 0.475 mol%; the result is useful as a peak-screening fit example but is not interpreted as independent model validation.

4.4.2. Data-sufficiency threshold sensitivity

The Yang et al. [7] Ho^{3+} series satisfies the concentration-point criterion under the relaxed, reference, and strict scenarios. However, system-level QPI/PSO analysis was not performed because sufficiently complete high-temperature optical calibration and sensor-regime k(c,T) data are not available together for the same system.

This result shows that the decision not to apply QPI/PSO does not depend solely on the reference threshold values; the same data gaps persist under reasonable changes in threshold stringency.

4.5. Comparison of available and missing evidence

Comparison of the six ions shows marked differences in evidence coverage. Concentration–photoluminescence references are available for Tm^{3+}, Ho^{3+}, and Nd^{3+}, whereas turbine-window thermometry and direct SHM calibration are missing in the selected source set. Er^{3+} has high-temperature thermal-history and delamination evidence; Eu^{3+} has stress and delamination evidence; and Dy^{3+} has more extensive in-situ thermometry evidence.

Table 4. Comparison of available and missing evidence for the six candidates. N/A indicates that no data are available in the relevant temperature range, whereas 0% indicates that data exist but do not overlap the 1200–1500 K window. “SHM evidence” refers to direct or related optical measurement of stress or delamination within the same ion family and does not imply that all data groups correspond to the identical composition and process.

Activator	I(c) reference	1200–1500 K coverage C_T	Direct low-c k(c,T)	Related SHM evidence	Dominant evidence mode
Tm^{3+}	Available	N/A (no high-T data)	No	No	PL
Ho^{3+}	Available	N/A (no high-T data)	No	No	PL
Nd^{3+}	Available	N/A (no high-T data)	No	No	PL
Er^{3+}	No concentration optimum	~74%	No	Related/partial; delamination [18,19]	Thermal history + SHM
Eu^{3+}	No concentration optimum	0% (direct YSZ:Eu evidence below 1200 K)	No	Strong direct; stress + delamination [17,20]	In-situ thermometry + SHM
Dy^{3+}	No concentration optimum	~24%	No	No direct evidence in selected set	In-situ thermometry

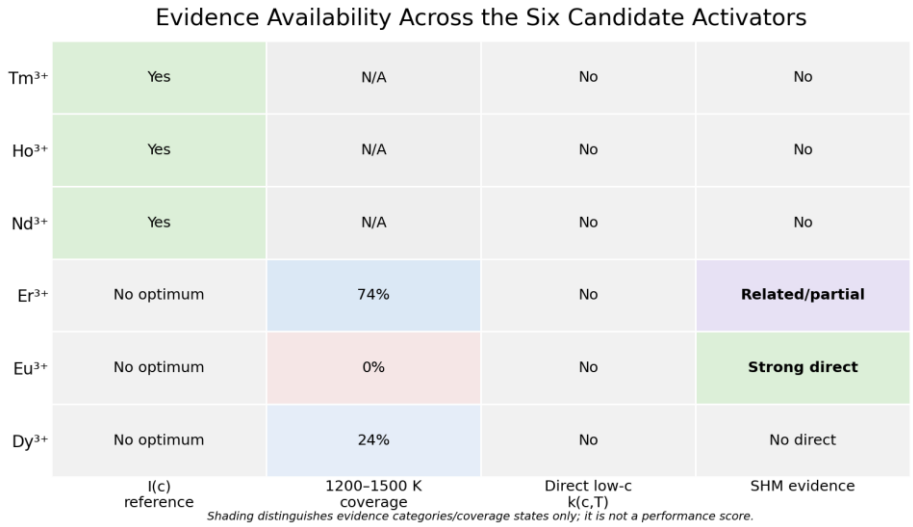


Figure 4. Visual summary of available and missing evidence for the six candidates. N/A indicates no data; 0% indicates that the available data do not overlap the 1200–1500 K window. SHM classes are the same as in Table 4. Cell shading is used only to distinguish evidence categories and coverage states; it is not a performance score.

5. Discussion

5.1. Assessment of the available evidence

Existing studies show that YSZ can serve as an optical host for different rare-earth ions and that measurable photoluminescence can be obtained at low dopant levels [5–8,14]. Because of concentration quenching, a higher dopant concentration does not always produce a stronger signal. Room-temperature PL behavior alone also does not represent high-temperature performance. Eu^{3+}-based stress and delamination studies, together with Er^{3+}/Yb^{3+}- and Er^{3+}-based delamination studies, show that the optical signal can be related to structural condition [17–20].

These findings support the addition of optical monitoring functionality to the thermal-protection role of a TBC. Continuous real-time multiparameter monitoring, however, has not yet been demonstrated for all six candidates on a rotating turbine blade under actual engine conditions in the 1200–1500 K range.

5.2. Complementary nature of the Tm^{3+}, Eu^{3+}, and Er^{3+} evidence

Tm^{3+} has distinct concentration–photoluminescence data [5]. Eu^{3+} has strong SHM evidence for stress and delamination [17,20]. Er^{3+} has high-temperature thermal-history data and delamination-monitoring studies [9,10,18,19]. These different evidence types show that no single ion can be assumed to be inherently superior for every function.

Two design strategies may be considered in future work. The first is a single-activator multifunctional coating in which one rare-earth ion provides both temperature and SHM functionality at an adequate level. The second is a multilayer sensor-TBC architecture in which the thermal-barrier top coat is separated from thin luminescent sublayers with different optical functions. The latter may be more realistic if an ion is optically effective but not ideal for the thermal-barrier role, or if different sensing functions require different ions [3,17–19].
Controlled experiments using the same production method and comparable microstructures are required to compare single-activator and multilayer architectures.

5.3. Missing data and conditions for applying PSO

Filling a missing data group with values measured for another ion or a different process could create artificial comparability among the candidates. Accordingly, unknown high-temperature optical response, stress sensitivity, or k(c,T) data were not transferred directly from other systems in this study. The data-sufficiency check was used to activate the multi-criteria calculation only when the required data groups are available together. Although the I(c) curve for Ho^{3+} reproduces the peak position with acceptable accuracy, high-temperature, thermal, and SHM data gaps remain.

5.4. Optical SHM mechanisms

Three main mechanisms are considered in the proposed optical SHM approach. The first is piezospectroscopic peak shift: stress alters the crystal field and changes the wavelength of specific luminescence transitions. After calibration, laser scanning can be used to generate a stress map at the surface or at a selected depth [20]. The second is luminescence-intensity contrast: cracks or delamination alter the optical path and can increase or decrease emission in the damaged region [17–19]. The third involves changes in lifetime and spectral ratio, which may be used together to help separate temperature and stress effects.
A single optical-intensity value is not sufficient for direct deformation measurement. Calibration between strain/stress and spectral peak position, an appropriate optical mapping geometry, and, when needed, finite-element-assisted mechanical reconstruction are required. SHM interpretation is therefore restricted to calibrated piezospectroscopic sensitivity and/or damage-contrast measurements.

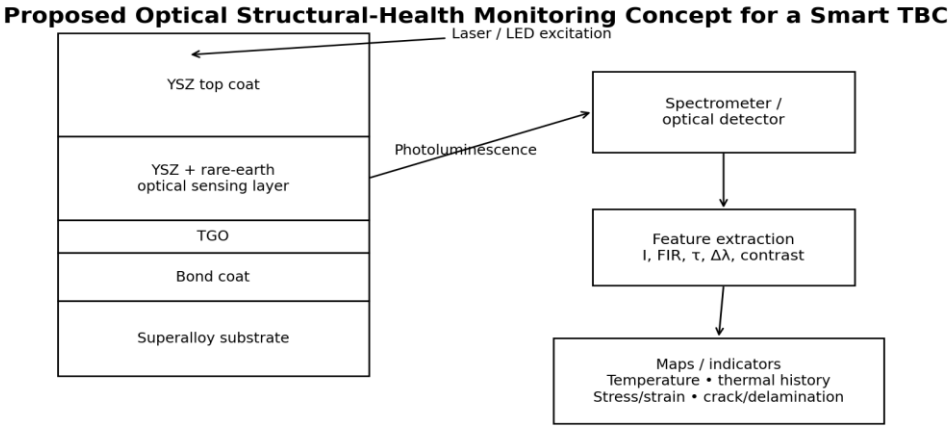


Figure 5. Proposed smart-TBC structural-health-monitoring concept. Optical excitation and photoluminescence acquisition can be converted, when suitable calibrations are available, into indicators of temperature/thermal history, stress, and crack/delamination.

6. Experimental Work Required for Full Optimization

Before a complete multi-criteria comparison can be performed, the missing data groups must be completed through targeted, mutually compatible experiments. The proposed experimental program is summarized below.

6.1. Experiment 1: Concentration–photoluminescence scan under identical conditions

The Tm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, Eu^{3+}, and Dy^{3+} candidates should, as far as possible, be prepared in the same YSZ host phase using the same production method. Denser concentration sampling should be performed

around the peak region reported for each candidate; for Tm^{3+}, this region is around 0.50 mol%. The same laser power, optical collection angle, specimen thickness, and detector settings should be used to obtain a genuine comparative optical-intensity data set across the candidates.

6.2. Experiment 2: High-temperature optical calibration over 1200–1500 K

The target measurement mode should be selected in advance for each candidate. For in-situ thermometry, FIR(T) or τ(T) should be calibrated; for thermal-history sensing, the relationship between permanent optical change and exposure temperature should be measured. High-temperature blackbody radiation, signal-to-noise ratio, and thermal quenching should also be reported.

6.3. Experiment 3: Stress/strain–photoluminescence calibration

Coating specimens should be subjected to controlled mechanical loading and/or thermal cycling. Spectral peak shift $\Delta\lambda_p$, linewidth, intensity, and lifetime changes should be measured simultaneously. The stress field should be validated by an independent method, such as XRD, digital image correlation where appropriate, or finite-element-assisted mechanical calibration. This experiment will make the S_σ value in Eq. (8) comparable among candidates.

6.4. Experiment 4: Controlled crack and delamination imaging

Delamination/crack regions with known size and location should be generated by Rockwell indentation, controlled interfacial defects, or thermal cycling. The contrast C_d between intact and damaged regions should be calculated from luminescence images, and the minimum detectable defect size should be established. The Eu^{3+} and Er^{3+} literature provides reference methods for this experiment [17–19]. Applying the same test to Tm^{3+} will determine whether its distinct emission near 458 nm offers an advantage for damage imaging.

6.5. Experiment 5: Thermal conductivity and coating durability in the sensor regime

The effects of low rare-earth additions on the thermal conductivity, phase stability, sintering behavior, and thermal-cycling life of YSZ should be measured within the same specimen family. k(c,T) should be determined at no fewer than two, preferably three, temperatures and at multiple concentrations. Optical performance should be evaluated together with the fundamental thermal-protection function of the TBC.

6.6. Experiment 6: Coating-scale and optical-access validation

Single-crystal data are valuable for screening but do not fully represent the scattering, porosity, and thickness effects of real TBC microstructures produced by APS, SPS, EB-PVD, or PS-PVD. The selected candidates should therefore be produced in realistic coating architectures, and top-coat thickness, luminescent-layer depth, and optical access should be evaluated systematically. Dynamic testing should then be performed at the hot-air-rig or burner-rig level.

Table 5. Proposed data package for six experimental stages followed by uncertainty analysis.

Stage	Quantity to be measured	Minimum objective	Role in PSO/QPI
1	I(c), spectrum, peak concentration	True optical comparison among ions in the same setup	I* and concentration range
2	FIR(T) or τ(T), 1200–1500 K	High-T thermometry / thermal-history validation	S_T*, τ*
3	$\Delta\lambda_p(\sigma)$ or equivalent	Stress/strain calibration	S_σ*
4	Damaged–intact luminescence image	Crack/delamination detection limit	C_d*
5	k(c,T), phase, and thermal cycling	Preservation of TBC function	(1 − k*), durability constraint
6	APS/EB-PVD/SPS coating-scale test	Real microstructure and optical access	Feasibility constraint
A	Repeat experiments and uncertainty assessment	Confidence interval and repeatability	E, Monte-Carlo / robust score

After this data package is completed, the MATLAB framework should fit the curves for each candidate, reproduce the literature reference peak values, and quantify uncertainties. Candidates satisfying the data-sufficiency criteria can then enter the extended QPI assessment; PSO may subsequently be applied to design variables such as dopant concentration and, where relevant, sensor-sublayer thickness. The final

stage should report weight sensitivity, bootstrap/Monte-Carlo uncertainty propagation, and PSO convergence.

7. Limitations

The main limitation of this study is the absence of a complete multiphysics data set collected under identical experimental conditions for all six candidates. Only one Ho^{3+} I(c) data set has been digitized and used in the curve-fitting test. The full ordinates of the Tm^{3+} and Nd^{3+} curves have not yet been digitized in the same manner. For Tm^{3+}, Ho^{3+}, and Nd^{3+}, high-temperature thermometry data within the turbine-relevant window are insufficient in the selected source set.

A second limitation is the unequal distribution of SHM evidence among the candidates. Strong direct evidence for stress and delamination is available for Eu^{3+}, while delamination-monitoring studies are available within the Er^{3+} family [18,19]. Comparable SHM calibrations are not available for Tm^{3+}, Ho^{3+}, Nd^{3+}, and Dy^{3+}.

A third limitation is the difference between single crystals and real coating microstructures. Porosity and scattering in APS coatings, the columnar structure of EB-PVD coatings, and the microstructure of SPS coatings can alter optical-signal access and mechanical behavior. The candidates therefore require additional coating-scale validation.

A fourth limitation is the presence of rotation, vibration, combustion radiation, surface contamination, optical-window durability, and line-of-sight constraints in actual engine environments. Accordingly, successful laboratory-scale in-situ optical measurement does not by itself imply readiness for continuous real-time monitoring in a flight engine.

8. Conclusions

7. The Tm^{3+}, Ho^{3+}, Nd^{3+}, Er^{3+}, Eu^{3+}, and Dy^{3+} systems were evaluated as separate sensor candidates; data from different studies were not merged into a single virtual-material data set.
8. Peak values of approximately 0.50 mol% for Tm^{3+}, approximately 0.50–0.75 mol% for Ho^{3+}, and approximately 0.75 mol% for Nd^{3+} are reported in the concentration–photoluminescence literature. For Tm^{3+}, the approximately 0.50 mol% value is a practical concentration reference for subsequent comparative experiments.
9. Er^{3+} provides strong evidence for high-temperature thermal-history sensing in the selected sources. Strong direct evidence for stress and delamination exists for Eu^{3+}, while experimental studies on delamination monitoring are available for the Er^{3+} family [17–20]. Dy^{3+} has broader high-temperature evidence for in-situ thermometry.
10. Curve fitting of the Ho^{3+} data of Yang et al. [7] yielded c_{peak} = 0.475 mol%, R^2 = 0.874, and RMSE = 0.068. This result shows that the peak position in the source graph can be reproduced; it is not interpreted as independent physical-model validation.
11. Because high-temperature FIR(T)/τ(T), low-dopant k(c,T), and candidate-specific SHM calibrations are not jointly available in the present data set, QPI/PSO-based material ranking was not performed.
12. The next stage should complete comparative PL measurements, high-temperature optical calibration, stress–peak-shift calibration, controlled crack/delamination imaging, thermal-conductivity measurements, and thermal-cycling tests using the same process and comparable coating architectures.

Declarations

Data and Code Availability: This study is based on a MATLAB computational framework and DOI-traceable study records. Six Ho^{3+} points approximately digitized from Figure 10 of Yang et al. [7] were used as normalized curve-fitting data. These are not raw spectrometer outputs, but relative ordinates approximately extracted from a published graph. The remaining high-temperature optical-response, SHM-calibration, and sensor-regime k(c,T) data groups should be digitized from verified sources or measured experimentally before a full comparison is undertaken.

Funding: This research received no external funding.

Conflict of Interest: The author declares no conflict of interest.

Author Contributions: Conceptualization, methodology development, computational framework, interpretation, and manuscript preparation: Mehmet Bakırcı.

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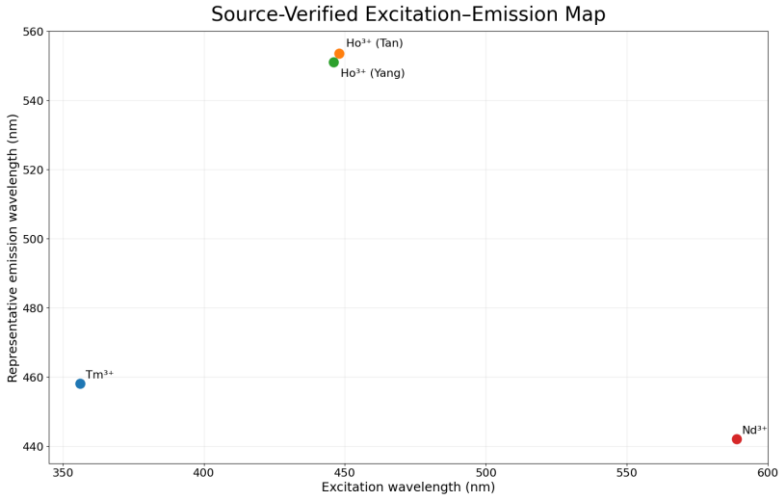
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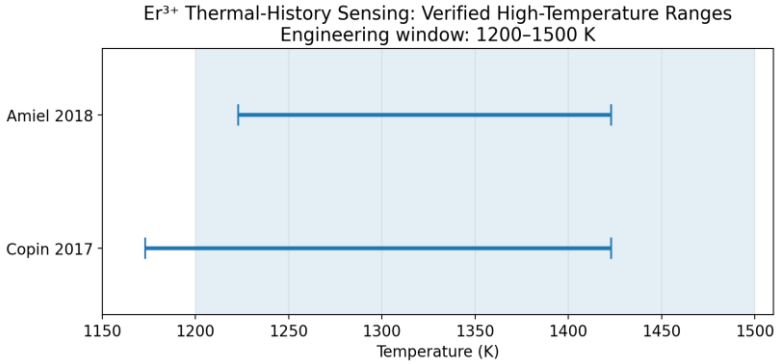
Appendix A. Next steps for data extraction and experiments

1. Six points from the Ho^{3+} I(c) series of Yang et al. [7] have been digitized and used with Eq. (4) for curve fitting and peak-position reproduction. The Ho^{3+} curve of Tan et al. [6] should be digitized as a separate study; the two Ho^{3+} series should not be merged into a single curve.
2. For Tm^{3+} and Nd^{3+}, concentration-dependent emission intensities should be digitized as complete curves, and the fitted peaks should be tested for reproduction of the literature reference values of approximately 0.50 and 0.75 mol%, respectively.
3. FIR(T) or τ(T) data should be generated experimentally for the candidates over 1200–1500 K.
4. For at least Tm^{3+}, Eu^{3+}, and Er^{3+}, stress-induced peak shift and controlled delamination/crack luminescence contrast should be measured using the same coating process.
5. Optical and thermal studies should be matched as closely as possible in terms of host phase and process to obtain k(c,T) data. If matching is not possible, a study-compatibility penalty should be applied.
6. Before material ranking, QPI weight sensitivity, bootstrap/Monte-Carlo uncertainty propagation, and PSO convergence tests should be performed.

Supplementary Figures



Supplementary Figure S1. Visual comparison of source-verified excitation–emission wavelengths in the principal Tm^{3+}, Ho^{3+}, and Nd^{3+} studies.



Supplementary Figure S2. Verified high-temperature ranges of the Er^{3+} thermal-history studies. These ranges are post-exposure thermal-history sensing intervals, not in-situ thermometry calibrations.

EFFECTIVENESS OF FLUID VISCOUS DAMPERS IN PREVENTING SOFT-STORY COLLAPSE UNDER NEAR-FAULT AND FAR-FAULT GROUND MOTIONS: A PERFORMANCE-BASED ASSESSMENT

YAKIN FAY VE UZAK FAY DEPREM KAYITLARI ALTINDA YUMUŞAK KAT GÖÇMESİNİN ÖNLENMESİNDE VİSKOZ SIVILI SÖNÜMLEYİCİLERİN ETKİNLİĞİ: PERFORMANS ESASLI BİR DEĞERLENDİRME

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ÖZET
Türkiye'de ve dünyadaki birçok deprem ülkesinde, yumuşak kat düzensizliğinin sebep olduğu yıkımlar ve ekonomik kayıplar halen ön sıralarda yer almaktadır. Çoğunlukla katlar arası önemli rijitlik farklarına sebep olan çeşitli mimari uygulamalar ile oluşan bu düzensizlik türü, deprem sonrası hasarların ilgili katta yoğunlaşarak büyük kalıcı yanal ötelemelere veya kat mekanizması ile göçmelere sebep olmaktadır. Özellikle dolgu duvarların sebep olduğu yumuşak kat düzensizliklerinde geleneksel doğrusal tasarım yaklaşımları söz konusu riskleri belirlemede yetersiz kalmaktadır. Bu nedenle yumuşak kat düzensizliği bulunan birçok binanın ileri yöntemlerle değerlendirilmesine ve gerekli durumlarda güçlendirilmesine ihtiyaç bulunmaktadır. Hasarın belirli bir katta yoğunlaştığı bu tür binalarda geleneksel güçlendirme yöntemlerinin kullanılması çoğu zaman pratik ve ekonomik olmamaktadır. Buna karşılık binadaki sönümü artırmayı hedefleyen viskoz sıvılı sönümleyici (VSS) cihazlar ile güçlendirme bölgesel güçlendirmeler için önemli bir potansiyele sahiptir. Bu çalışmada, betonarme bir bina modeli üzerinde yumuşak kat göçmesinin VSS'ler ile önlenebilirliği sayısal olarak incelenmiştir. Bunun için deprem yönetmeliğine uygun olarak tasarlanmış 4-katlı bir bina modeli ele alınmış ve zemin katındaki dolgu duvarların azaltılması ve kat yüksekliğinin artırılması suretiyle yumuşak kat düzensizliği oluşturulmuştur. Daha sonra bina modeli, sadece birinci katında bazı açıklıklara VSS'ler uygulanarak güçlendirilmiştir. Güçlendirme öncesi ve sonrası modeller, en büyük deprem yer hareketi düzeyine göre ölçeklenen uzak ve yakın fay karakteristiğine sahip iki grup deprem kaydı için doğrusal olmayan dinamik analiz ile performans-esaslı yaklaşım çerçevesinde değerlendirilmiştir. Çalışmada maksimum ve kalıcı göreli kat öteleme oranları ve plastik dönmelere ait talep/kapasite oranları incelenmiştir. Uzak fay grubundaki kayıtlar için oluşan tüm göçme durumları VSS'ler sayesinde önlenebilirken, yakın fay grubuna ait bazı kayıtlarda VSS kapasiteleri artırılmasına rağmen göçme oluşumu engellenememiştir. VSS kullanımı, yumuşak kat düzensizliği bulunan kattaki maksimum ve kalıcı göreli kat öteleme oranlarını azaltarak uzak fay grubundaki depremler için hasarları *Göçmenin Önlenmesi* performans düzeyine çekebilmiş, ancak yakın fay depremlerinde ise hasarlar bir üst katta yoğunlaşmış ve öngörülen performans düzeyi sağlanamamıştır.
Anahtar kelimeler: Yumuşak kat düzensizliği, Göçmenin Önlenmesi, Vizkoz sıvılı sönümleyici, Betonarme bina, Performans-esaslı sismik değerlendirme

ABSTRACT
Soft-story irregularity remains one of the major causes of structural collapse and associated economic losses in Türkiye and other earthquake-prone regions worldwide. This type of vertical irregularity commonly results from architectural and functional requirements that produce a substantial difference in lateral stiffness between adjacent stories. During strong earthquakes, deformation and damage can consequently become concentrated in the soft story, leading to large permanent lateral displacements and, in severe cases, a story-level collapse mechanism. This vulnerability may not be adequately identified by conventional linear design approaches, particularly in buildings where the soft-story condition is primarily associated with reduced infill walls. Therefore, advanced performance-based assessment and, where necessary, effective retrofit strategies are required for such buildings. Conventional strengthening methods may be impractical or uneconomical when damage is highly

localized in a particular story. In contrast, fluid viscous dampers (FVDs), which enhance supplemental energy dissipation, may provide an efficient alternative for localized seismic retrofit. This study numerically investigates the feasibility of preventing soft-story collapse in a reinforced concrete building using FVDs. A four-story reinforced concrete building designed in accordance with the seismic design provisions was considered as the reference structure. A soft-story irregularity was subsequently introduced at the ground story by reducing the amount of infill walls and increasing the story height. The resulting structure was then retrofitted by installing FVDs in selected bays of the ground story only. The unretrofitted and retrofitted models were evaluated using nonlinear response-history analyses under two groups of ground motions representing far-fault and near-fault earthquake characteristics, scaled to the maximum considered earthquake level. The seismic performance was assessed in terms of maximum and residual interstory drift ratios and plastic rotation demand-to-capacity ratios. The results indicate that all collapse cases observed under the far-fault ground-motion group could be prevented by the use of FVDs. However, collapse could not be prevented for some of the near-fault ground motions even when the damper capacities were increased. For the far-fault records, the FVDs substantially reduced both maximum and residual interstory drift ratios in the soft story and shifted the structural damage level to the Collapse Prevention performance level. For the near-fault records, however, the reduction in deformation demand at the soft story was accompanied by a redistribution of damage toward the story immediately above it, and the target performance level could not be consistently achieved.
Keywords: Soft-story irregularity; Collapse Prevention; Fluid viscous dampers; Reinforced concrete buildings; Performance-based seismic assessment

GİRİŞ

Yumuşak kat düzensizliği, özellikle zemin katta dolgu duvarların azaltılması veya kaldırılması ve kat yüksekliğinin artırılması gibi mimari uygulamalar sonucunda oluşan önemli bir düşey düzensizlik türüdür. Katlar arasındaki yatay rijitlik ve dayanım farkının artması, deprem etkisi altında deformasyonların düzensizliğin bulunduğu katta yoğunlaşmasına ve ileri hasar durumunda kat mekanizmasıyla göçmeye neden olabilmektedir. Türkiye'de 1999 Kocaeli ve Düzce depremleri ile 2023 Kahramanmaraş depremlerinde gözlenen ağır hasar ve göçmeler, zemin kat düzensizliklerinin deprem güvenliği açısından önemli bir sorun oluşturduğunu göstermiştir (Erdik, 2000; AFAD, 2023). Dolgu duvarların yapı davranışına etkisini inceleyen çalışmalar da bu tür rijitlik farklılıklarının yumuşak kat mekanizmasını belirgin biçimde etkileyebildiğini ortaya koymaktadır (Dolšek & Fajfar, 2001; Fardis & Panagiotakos, 1997). Benzer şekilde, farklı yumuşak kat oluşum biçimlerinin betonarme yapıların sismik davranışı üzerindeki etkisi sayısal olarak da gösterilmiştir (Özmen vd., 2020).



Şekil 1. Yumuşak kat nedeniyle oluşan göçme örnekleri (AFAD, 2023)

Yumuşak kat oluşumundaki temel problem, deprem sırasında yatay ötelenme ve plastik şekil değiştirmelerin belirli bir katta yoğunlaşmasıdır. Özellikle güçlü yer hareketlerinde bu durum kat mekanizmasına ve nihai olarak göçmeye dönüşebilmektedir. Bu nedenle yumuşak katlı yapıların değerlendirilmesinde yalnızca dayanım kontrollerinin değil, deprem taleplerinin deformasyon ve hasar düzeyleri açısından da incelendiği performans esaslı yaklaşımların kullanılması önemlidir.

Yumuşak katlı yapıların güçlendirilmesinde kolon mantolama, perde, çerçeve ekleme veya çapraz çelik çaprazlar ekleme gibi geleneksel yöntemler kullanılabilmektedir. Ancak bu yöntemler yapının rijitlik ve dayanım dağılımını önemli ölçüde değiştirebilmekte, mimari kullanımın kısıtlanmasına veya yapının diğer bölümlerinde ilave müdahalelere neden olabilmektedir. Bu nedenle, deprem enerjisinin taşıyıcı sistem yerine, ilave enerji tüketim elemanları aracılığıyla sönümlenmesini sağlayan pasif kontrol sistemleri önemli bir alternatif oluşturmaktadır (Symans vd., 2008). Bunlar arasında önemli yer tutan viskoz sıvılı sönümleyiciler (VSS), hıza bağlı sönüm kuvveti oluşturarak yapıya önemli enerji tüketme kapasitesi kazandırabilmekte ve mevcut taşıyıcı elemanlarda kapsamlı değişiklik yapılmadan sismik taleplerin karşılanmasına olanak sağlamaktadır.

Yumuşak katlı betonarme yapıların enerji tüketen sistemlerle güçlendirilmesine yönelik çalışmalar, bu yaklaşımın özellikle kat öteleme ve plastik şekil değiştirme taleplerinin azaltılmasında etkili olabileceğini göstermektedir. Benavent-Climent ve Mota-Páez (2017) ile Oinam ve Sahoo (2018), yumuşak birinci kata sahip betonarme çerçevelerde pasif enerji tüketen sistemlerin kullanımının sismik performansı iyileştirebildiğini göstermiştir. Jara vd. (2020) ise 19 Eylül 2017 Mexico City depreminde gözlenen yumuşak katlı betonarme bina hasarlarını incelemiş ve mevcut ilk katı yumuşak yapıların güçlendirilmesinde enerji tüketen sistemlerin kullanımını değerlendirmiş ve çeşitli sistemlerin performanslarını karşılaştırmıştır. Çakıl vd. (2026), yumuşak kat düzensizliği bulunan betonarme yapılarda farklı güçlendirme yöntemlerini karşılaştırmış ve viskoz sönümleyicilerin yapısal taleplerin azaltılmasındaki etkinliğini diğer güçlendirme seçenekleriyle birlikte değerlendirmiştir.

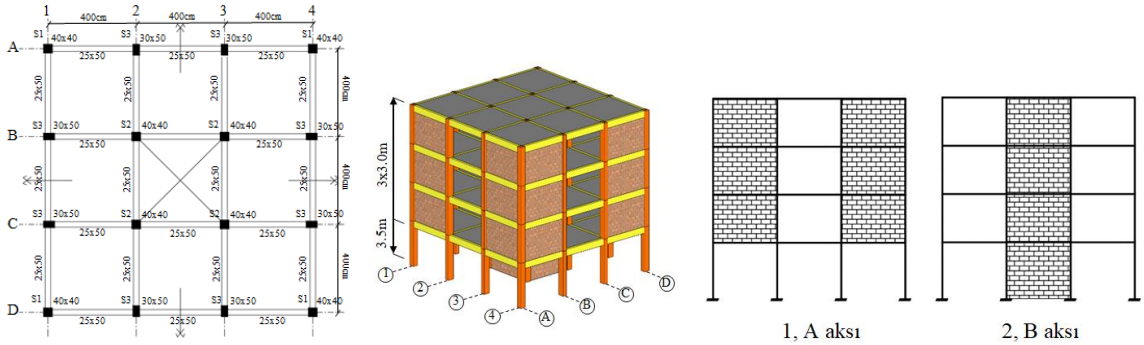
Bununla birlikte, yumuşak katlı bir yapıda sönümleyicilerin yalnızca düzensizliğin bulunduğu kata yerleştirilmesi, deformasyon taleplerinin üst katlara aktarılmasına neden olabilmektedir. Ayrıca yakın fay hareketlerinde görülebilen yüksek hız darbeleri ve farklı enerji içerikleri, yapının ve enerji tüketim sisteminin davranışını uzak fay kayıtlarından farklılaştırabilmektedir. Yumuşak birinci kata sahip betonarme çerçevelerin enerji tüketen sistemlerle güçlendirilmesini yakın fay depremleri altında inceleyen çalışmalar da bu farklılığın dikkate alınması gerektiğini göstermektedir (Mota-Páez vd., 2021). Dolayısıyla VSS kullanımının yumuşak kat göçmesini önlemedeki etkinliğinin farklı deprem karakteristikleri altında ve yapı genelindeki performans dikkate alınarak değerlendirilmesi önem taşımaktadır.

Bu çalışmada, TBDY-2018'e göre tasarlanan dört katlı bir betonarme binada oluşturulan yumuşak kat düzensizliğinin VSS'ler ile giderilerek *Göçmenin Önlenmesi* performans düzeyinin sağlanabilirliği, yakın fay ve uzak fay karakteristiğine sahip deprem kayıtları altında incelenmiştir. Yumuşak kat, zemin kattaki dolgu duvarların azaltılması ve kat yüksekliğinin artırılmasıyla oluşturulmuş ve VSS'ler yalnızca birinci kattaki seçilmiş açıklıklara yerleştirilmiştir. Güçlendirme öncesi ve sonrası bina modellerinin doğrusal olmayan dinamik analizleri TBDY-2018 kapsamında değerlendirilmiş, maksimum ve kalıcı göreli kat öteleme oranları ile plastik dönme talep/kapasite oranları kullanılarak en büyük deprem yer hareketi düzeyi için *Göçmenin Önlenmesi* performans düzeyinin sağlanabilirliği araştırılmıştır.

SAYISAL İNCELEME

İncelenen Bina Modeli ve Tasarım Özellikleri

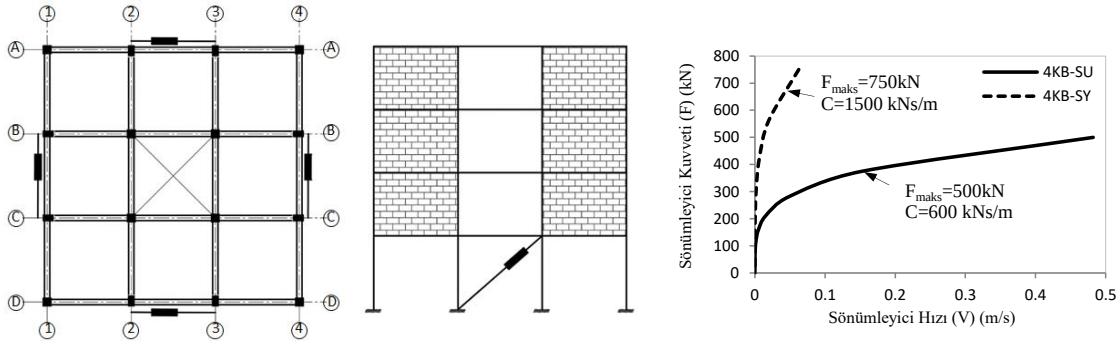
Çalışmada, yumuşak kat düzensizliği nedeniyle oluşan *Göçmenin Önlenmesi*nde viskoz sıvılı sönümleyicilerin (VSS) etkinliğini incelemek amacıyla dört katlı bir bina modeli ele alınmıştır. İncelenen bina modelinin üç boyutlu görünümü, tipik kat planı ve dolgu duvar düzeni Şekil 2'de gösterilmiştir. Yumuşak kat davranışını temsil etmek amacıyla zemin katın özellikleri üst katlardan farklılaştırılmıştır. Bu kapsamda, zemin kat yüksekliği artırılmış ve bu katta bulunan dolgu duvarların bir bölümü kaldırılmıştır. Böylece komşu katlar arasında yatay rijitlik ve deformasyon kapasitesi bakımından belirgin bir farklılık oluşturularak deprem etkisi altında deformasyonların zemin katta yoğunlaşmasına elverişli bir taşıyıcı sistem elde edilmiştir. Bina, kullanım amacı konut olarak alınmış, yüksek süneklik sınıfını sağlayacak şekilde 2007 Türkiye Deprem Yönetmeliğine göre tasarlanmıştır (Bayındırlık ve İskân Bakanlığı, 2007). Tasarımda dolgu duvarların ağırlıkları göz önüne alınmış, rijitlik ve kapasiteleri ihmal edilmiştir. Tasarım sonuçlarına ait detaylı bilgi Aşıcı (2025)'de bulunabilir.



Şekil 2. Bina tipik kat planı, üç boyutlu görünümü ve dolgu duvar düzenleri

Doğrusal Olmayan Sayısal Modelleme ve Analiz Özellikleri

Çalışmada güçlendirme öncesini temsil eden bir model (4KB) ve VSS'ler ile güçlendirilmiş binaları temsilen iki model oluşturulmuştur. VSS'ler sadece zemin katta ve kenar akslardaki orta açıklıklara uygulanmıştır (Şekil 3). VSS'ler hız bağımlı sönüm kuvveti oluşturan doğrusal olmayan kuvvet–hız bağıntısı kullanılarak modellenmiştir. Uzak ve yakın fay grubundaki kayıtlar için ayrı ayrı analiz yapılarak TBDY-2018'e göre *Göçmenin Önlenmesi* performans düzeyini sağlamak üzere VSS özellikleri araştırılmıştır. Buna göre güçlendirme öncesi için oluşturulan modele farklı kuvvet ve sönüm kapasitelerine sahip VSS'ler kullanılmış ve uzak fay grubuna ait model 4KB-SU, yakın fay grubuna ait model 4KB-SY olarak adlandırılmıştır (Şekil 3). Tüm modellerde kolon ve kirişlerin doğrusal olmayan davranışları yığılı plastisite yaklaşımı ile temsil edilmiş ve ASCE/SEI 41-17'ye göre belirlenen moment-plastik dönme bağıntıları kullanılmıştır (ASCE, 2017). Kolonlarda iki eksenli bileşik eğilme etkileri göz önüne alınmıştır. Dolgu duvarlar, yalnızca basınç kuvveti taşıyan iki ucu mafsallı eşdeğer diyagonal çubuklarla temsil edilmiş ve bunlara ait kuvvet–deformasyon ilişkileri TBDY-2018 (AFAD, 2018) esas alınarak tanımlanmıştır. Düğüm noktaları ve döşemeler için doğrusal davranış kabul edilmiş, döşemelerin düzlem içi rijitliği diyafram davranışı ile modele yansıtılmıştır. Analizlerde PERFORM-3D (CSI, 2023) programı kullanılmıştır. Doğrusal olmayan modellemeye ait detaylı bilgi Aşıcı (2025)'de bulunmaktadır.



Şekil 3. VSS'lerin planda ve düşey kesitteki yerleşimi ve kuvvet-hız ilişkisi

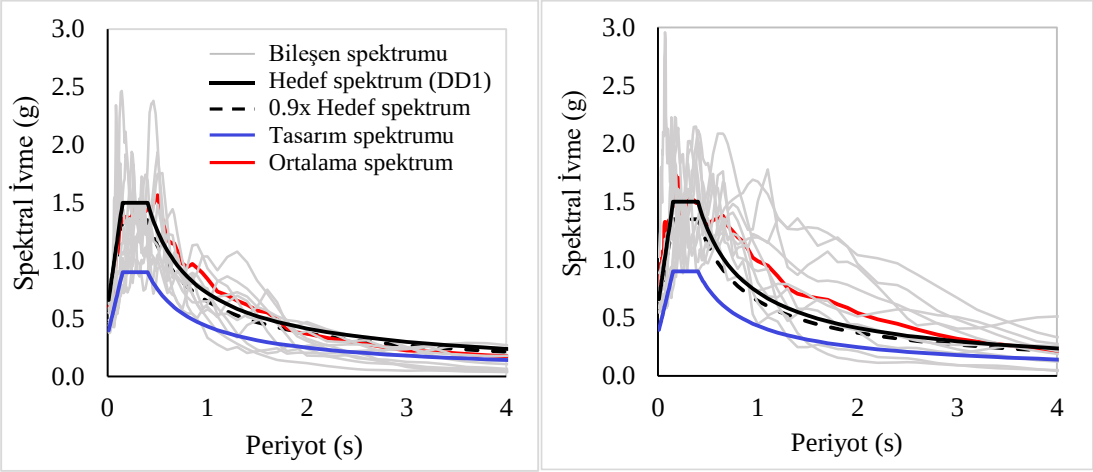
VSS'lerin hıza önemli ölçüde duyarlı olmaları nedeniyle çalışmada uzak ve yakın fay karakteristiğine sahip iki ayrı grup oluşturulmuştur. Bu kayıtlara ait temel özellikler Tablo 1,2'de verilmiştir (PEER, 2024). Çalışmada, en büyük (maksimum) deprem yer hareketi düzeyi (DD-1) için *Göçmenin Önlenmesi* performans düzeyinin sağlanabilirliği araştırıldığı için seçilen kayıtlar, tasarım deprem düzeyinin (DD-2) spektral olarak 1.5 katı olarak kabul edilen hedef spektruma göre genlik ölçekleme yaklaşımı ile ölçeklenmiştir (Şekil 4) (ASCE, 2023).

Tablo 1. Uzak fay deprem grubuna ait özellikler

Kayıt No	PEER Kodu	Deprem İsmi	Büyüklük	Fay Mekanizması	Faya Uzaklık Rjb (km)	Vs30 (m/s)	Maks. Yer İvmesi (g)	
							Bileşen-x	Bileşen-y
1	68	San Fernando	6.61	Ters Fay	22.8	316.5	0.225	0.195
2	125	Friuli_ Italy-01	6.5	Ters Fay	15.0	505.2	0.357	0.315
3	169	Imperial Valley-06	6.53	Ters Fay	22.0	242.1	0.236	0.350
4	900	Landers	7.28	Ters Fay	23.6	353.6	0.245	0.152
5	953	Northridge-01	6.69	Ters Fay	9.4	355.8	0.443	0.488
6	1111	Kobe_ Japan	6.9	Yanal Atımlı Fay	7.1	609.0	0.483	0.464
7	1158	Kocaeli_ Turkey	7.51	Yanal Atımlı Fay	13.6	281.9	0.312	0.364
8	1244	Chi-Chi_ Taiwan	7.62	Eğim Atımlı Ters Fay	9.9	258.9	0.34	0.364
9	1602	Duzce_ Turkey	7.14	Yanal Atımlı Fay	12.0	293.6	0.739	0.806
10	1633	Manjil_ Iran	7.37	Yanal Atımlı Fay	12.6	724.0	0.515	0.497
11	1787	Hector Mine	7.13	Yanal Atımlı Fay	10.4	726.0	0.266	0.329

Tablo 2. Yakın fay deprem grubuna ait özellikler

Kayıt No	PEER Kodu	Deprem İsmi	Büyüklük	Fay Mekanizması	Faya Uzaklık Rjb (km)	Vs30 (m/s)	Maks. Yer İvmesi (g)	
							Bileşen-x	Bileşen-y
12	126	Gazli_USSR	6.8	Ters Fay	3.92	259.5	0.702	0.864
13	160	Imperial Valley-06	6.53	Yanal Atımlı Fay	0.44	223.0	0.599	0.777
14	292	Irpinia_Italy-01	6.9	Düz Fay	6.78	382.0	0.227	0.321
15	495	Nahanni_Canada	6.76	Ters Fay	2.48	605.0	1.108	1.201
16	723	Superstition Hills-02	6.54	Yanal Atımlı Fay	0.95	348.6	0.432	0.384
17	741	Loma Prieta	6.93	Eğim Atımlı Ters Fay	3.85	476.5	0.456	0.502
18	821	Erzican_ Turkey	6.69	Yanal Atımlı Fay	0	352.0	0.496	0.387
19	828	Cape Mendocino	7.01	Ters Fay	0	422.1	0.591	0.662
20	1503	Chi-Chi_ Taiwan	7.62	Eğim Atımlı Ters Fay	0.57	305.8	0.790	0.576
21	1605	Duzce_ Turkey	7.14	Yanal Atımlı Fay	0	281.8	0.404	0.400
22	2114	Denali_ Alaska	7.9	Yanal Atımlı Fay	0.18	329.4	0.333	0.297



Şekil 4. Uzak (sol) ve yakın (sağ) fay deprem grupları için ölçeklenmiş ivme spektrumları ve tasarım spektrumu

Analiz Sonuçları

Uzak ve yakın fay gruplarındaki toplam 22 kayıt için iki doğrultulu olarak gerçekleştirilen doğrusal olmayan dinamik analizler sonucunda güçlendirme öncesi ve sonrası modellerde göçme oluşan ve

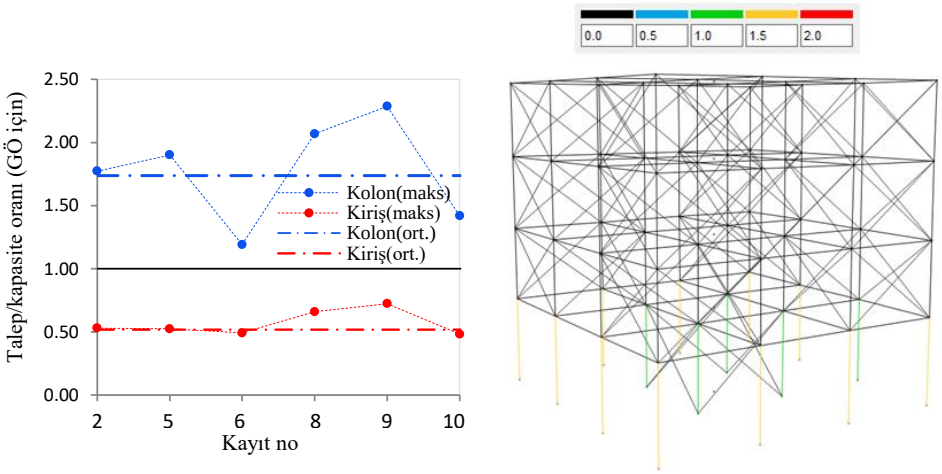
oluşmayan durumlar Tablo 3'de gösterilmiştir. Güçlendirme öncesi yumuşak düzensizliği bulunan modelde (4KB) uzak fay grubundaki 5 deprem kaydı için göçme oluşurken, yakın fay gubunda bu sayı 9'a çıkmıştır. Uzak fay grubu için VSS ile yapılan güçlendirme sonucunda tüm göçme durumları engellenmiş ve TBDY-2018'e göre *Göçmenin Önlenmesi* performans düzeyi sağlanmıştır. Yakın fay grubu için ise düzensizliğin bulunduğu kattaki deformasyonlar VSS'ler ile kontrol altına alınmasına rağmen üst katlardaki deformasyonlar nedeniyle 5 adet deprem kaydında göçme durumu oluşmuştur.

Tablo 3. Güçlendirme öncesi ve sonrası göçme oluşan ve oluşmayan kayıtlar

Uzak fay grubu			Yakın fay grubu		
Kayıt adı	4KB	4KB-SU	Kayıt adı	4KB	4KB-SY
San Fernando	Göçme	✓	Gazli_ USSR	Göçme	✓
Friuli_ Italy-01	✓	✓	Imperial Valley-06	✓	✓
Imperial Valley-06	Göçme	✓	Irpinia_ Italy-01	Göçme	✓
Landers	Göçme	✓	Nahanni_ Canada	Göçme	✓
Northridge-01	✓	✓	Superstition Hills-02	Göçme	Göçme
Kobe_ Japan	✓	✓	Loma Prieta	✓	✓
Kocaeli_ Turkey	Göçme	✓	Erzican_ Turkey	Göçme	Göçme
Chi-Chi_ Taiwan	✓	✓	Cape Mendocino	Göçme	✓
Duzce_ Turkey	✓	✓	Chi-Chi_ Taiwan	Göçme	Göçme
Manjil_ Iran	✓	✓	Duzce_ Turkey	Göçme	Göçme
Hector Mine	Göçme	✓	Denali_ Alaska	Göçme	Göçme
✓: Göçme oluşmadan tamamlanan analiz.					

Talep/kapasite oranları

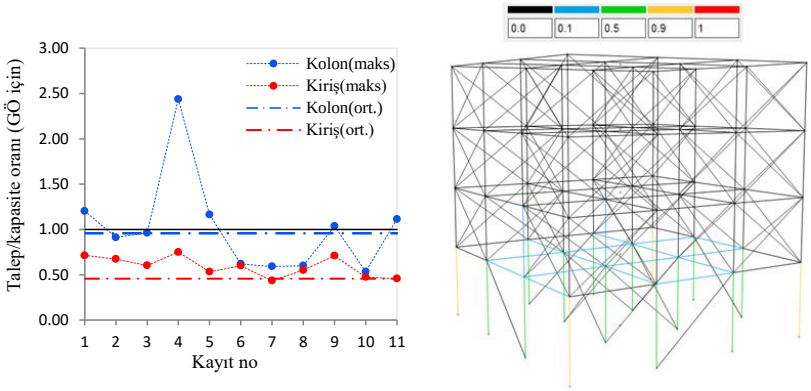
Güçlendirme öncesi modelde (4KB), göçmeler genellikle yumuşak katta meydana gelen mekanizma ile veya kolon dönme kapasitesinin aşılması nedeniyle oluşmuştur. Göçme durumu oluşmayan 6 deprem kaydının her biri için tüm elemanlardaki en elverişsiz (maks.) plastik dönme talepleri, *Göçmenin Önlenmesi* performans düzeyine ait sınırlara oranlanarak için talep/kapasite oranları belirlenmiş ve Şekil 5'te gösterilmiştir. Ayrıca, talep/kapasite oranlarının sistem elemanlarındaki karşılıkları ortalama değerler üzerinden renklendirilmiş ölçek ile Şekil 5'te verilmiştir. Tüm kolonlarda ve kayıtlarda *Göçmenin Önlenmesi* düzeyine karşılık gelen plastik dönme talepleri önemli oranda aşılmış, 6 kayıt için en elverişsiz değerlere ait ortalama talep/kapasite oranı 1.75 elde edilmiştir. Kirişlerde ise tüm kayıtlarda 1.0'in altında oranlar elde edilmiş, ortalama oran 0.5 elde edilmiştir.



Şekil 5. 4KB modelinde 6 uzak fay grubu deprem kaydı için talep/kapasite oranları

Uzak fay deprem grubu için güçlendirilen modele (4KB-SU) için elde edilen talep/kapasite oranları Şekil 6'da verilmiştir. VSS kullanımı ile düzensizliğin bulunduğu kattaki plastik dönme taleplerinin

kapasiteye oranları ortalamada kolonlar için 1.0'e çok yakın elde edilirken, kirişler için yaklaşık 0.5 elde edilmiştir. 4 adet kayıtta kolonlardaki maksimum oran 1.0'i aşmıştır. Kirişlerde ise maksimum oran 0.70 elde edilmiştir. En elverişsiz talep/kapasite oranları köşe kolonlarda elde edilmiş, diğer kolonlarda oranlar genellikle 0.50-0.90 arasında kalmıştır. 2. Katta sadece 2 adet kolonda 0.10'luk oran aşılmış, diğer elemanlar ya plastikleşmemiş ya da talep/kapasite oranları 0.10'un altında kalmıştır.

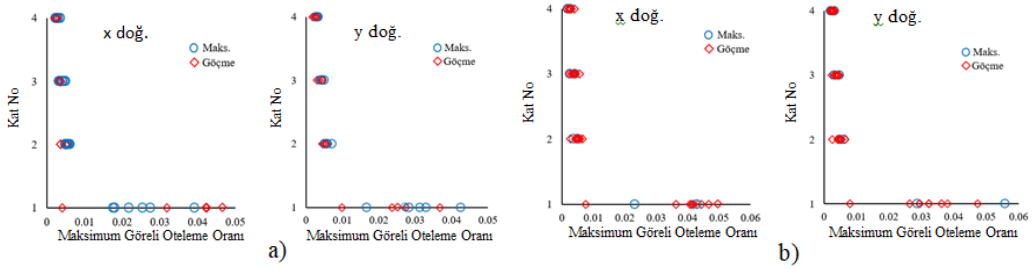


Şekil 6. Uzak fay grubu için güçlendirilmiş modelde (4KB-SU) talep/kapasite oranları

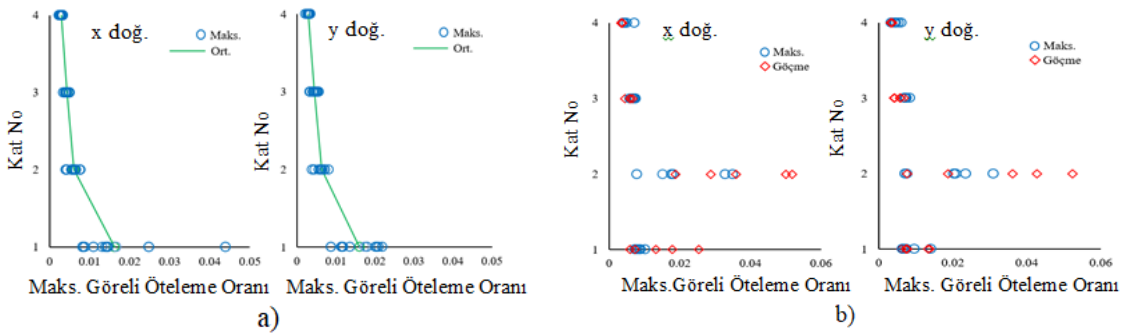
Maksimum göreli kat ötelemesi oranları

Güçlendirme öncesi model (4KB) için uzak ve yakın fay grubu kayıtlarından elde edilen maksimum göreli kat ötelemesi oranları x ve y doğrultuları için Şekil 7'de verilmiştir. Grafiklerde göçme durumu kayıtlar için analiz sonlanmadan önce elde edilen maksimum göreli kat ötelemesi oranları kırmızı ile gösterilmiştir. Şekil 7'den görüldüğü gibi, göçme oluşmayan depremlerde dahi düzensizliğin bulunduğu kattaki göreli kat ötelemesi oranları uzak fay için % 2-4 arasında, yakın fay için %2-6 arasında elde edilmiştir. Göçme oluşan durumlarda da göçme öncesi benzer öteleme oranları gözlenmiş ve sonrasında mekanizma ve/veya kapasite sonlanması nedeniyle analiz tamamlanamıştır.

Uzak fay ve yakın fay grubu depremler için güçlendirilen 4KB-SU ve 4KB-SY modellerinde elde edilen maksimum göreli öteleme oranları Şekil 8'de verilmiştir. 4KB-SU modelinde sadece 2 kayıt için maksimum oranlar %2.0'yi aşmış, buna karşılık düzensizliğin bulunduğu kata ait oran % 2.0'nin altında kalmıştır (Şekil 8a).



Şekil 7. Güçlendirme öncesi modelde(4KB) maks. göreli kat öteleme oranları a) Uzak fay grubu, b) Yakın fay grubu



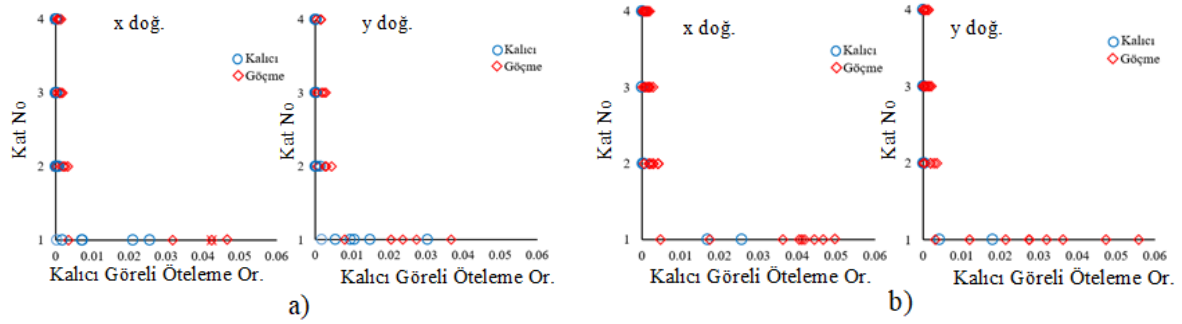
Şekil 8. Güçlendirilen modellerde maks. göreli kat öteleme oranları a) Uzak fay grubu (4KB-SU), b) Yakın fay grubu (4KB-SY)

Yakın fay grubu için güçlendirilen 4KB-SY modelinde de kullanılan VSS'ler ile düzensizliğin bulunduğu kattaki ötelemeler kontrol altına alınmış, ancak bir üst kattaki ötelemelerin önemli ölçüde artması nedeniyle *Göçmenin Önlenmesi* performans düzeyi sağlanamamış veya göçme durumu oluşmuştur. Buna göre 4KB-SY modelinde maksimum deprem düzeyi için VSS'ler ile göçmenin tamamen önlenebilirliği sağlanamamıştır.

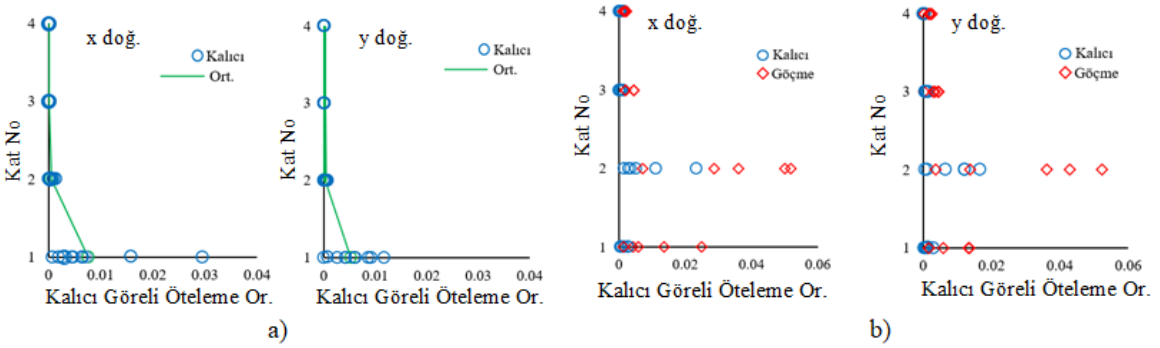
Kalıcı göreli kat öteleme oranları

Güçlendirme öncesi model (4KB) için uzak ve yakın fay grubu kayıtlarından elde edilen kalıcı göreli kat ötelemesi oranları x ve y doğrultuları için Şekil 9'da verilmiştir. Yumuşak kat düzensizliğinin bulunduğu katta kalıcı ötelemeler göçme oluşmayan durumlarda %3.0'lere, göçme gözlenen durumlarda ise göçme öncesinde %6.0'lara ulaşmıştır.

Uzak fay ve yakın fay grubu depremler için güçlendirilen 4KB-SU ve 4KB-SY modellerinde elde edilen kalıcı göreli öteleme oranları Şekil 10'da verilmiştir. *Göçmenin Önlenmesi* performans düzeyinin sağlandığı uzak fay deprem grubu için ortalama kalıcı öteleme oranları her iki doğrultu için de %1.0'in altında kalmıştır. Sadece 2 kayıt için %1.0'lik kalıcı göreli öteleme oranı aşılmıştır. En büyük deprem yer hareketi düzeyi (DD-1) için elde edilen bu sonuçların, eleman hasar düzeylerini temsil eden *Göçmenin Önlenmesi* performans düzeyi ile uyumlu olduğu söylenebilmektedir. Yakın fay grubu için güçlendirilen modelde VSS'ler ile düzensizliğin bulunduğu kattaki kalıcı göreli öteleme oranları büyük ölçüde kontrol altına alınmakla birlikte 2. katta oluşan kalıcı öteleme oranları bazı kayıtlarda göçmeye yol açmış bazı kayıtlarda ise öngörülen performansın çok üzerinde plastik dönmelere sebep olmuştur.



Şekil 9. Güçlendirme öncesi modelde(4KB) Kalıcı göreli kat öteleme oranları a) Uzak fay grubu, b) Yakın fay grubu



Şekil 10. Güçlendirilen modellerde kalıcı göreli kat öteleme oranları a) Uzak fay grubu (4KB-SU), b) Yakın fay grubu (4KB-SY)

SONUÇLAR VE ÖNERİLER

Bu çalışmada, yumuşak kat düzensizliği bulunan dört katlı betonarme bir bina modelinin en büyük deprem yer hareketi (DD-1) düzeyindeki uzak ve yakın fay karakteristiğine sahip deprem kayıtları altındaki performansı ve yalnızca yumuşak katta uygulanan viskoz sıvılı sönümleyicilerin (VSS) göçmeyi önlemedeki etkinliği incelenmiştir. Elde edilen sonuçlar genel olarak aşağıda verilmiştir.

Güçlendirme öncesi 4KB modelinde yumuşak kat düzensizliği, özellikle yakın fay kayıtlarında yüksek maksimum ve kalıcı göreli kat ötelemelerine ve yaygın göçme durumlarına neden olmuştur. Uzak fay grubunda 11 kaydın 5'inde, yakın fay grubunda ise 9'unda göçme meydana gelmiştir.

VSS uygulaması, her iki deprem grubunda da yumuşak kattaki deformasyon taleplerini belirgin biçimde azaltmıştır. Uzak fay grubunu temsil eden 4KB-SU modelinde tüm göçme durumları önlenmiş ve Göçmenin Önlenmesi performans düzeyi sağlanmıştır. Buna karşılık yakın fay grubunda 4KB-SY modeliyle yumuşak kattaki talepler kontrol altına alınmasına rağmen bazı kayıtlarda göçme devam etmiş ve hedeflenen performans düzeyi sağlanamamıştır.

Sonuç olarak, incelenen bina modeli ve deprem kayıtları kapsamında VSS'ler, özellikle uzak fay karakteristiğine sahip yer hareketleri altında yumuşak kat göçmesinin önlenmesi açısından etkili bir güçlendirme seçeneği olmuştur. Ancak yakın fay hareketlerinde elde edilen sonuçlar, sönümleyici kapasitesinin artırılmasının ve sadece düzensizlik bulunan katta kullanımın yeterli olmayabileceğini göstermiştir.

Gelecek çalışmalarda değerlendirmelerin farklı kat sayılarına, bina geometrilerine, taşıyıcı sistem özelliklerine ve yumuşak kat oluşum biçimlerine sahip bina modelleri için genişletilmesi önerilmektedir. Ayrıca VSS'lerin global bina davranışına etkisinin yanı sıra, sönümleyicilerin bağlandığı kolon, kiriş ve bağlantı bölgelerinde oluşturduğu lokal iç kuvvet ve deformasyon taleplerinin ayrıntılı olarak incelenmesi gerekmektedir. Özellikle yakın fay hareketlerinde deformasyon taleplerinin üst katlara yeniden dağılımı, farklı VSS yerleşimleri, sönümleyici kapasiteleri ve güçlendirme stratejileri açısından araştırılmalıdır.

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TALAŞLI İMALATTA DİJİTAL ÜRÜN PASAPORTU VE KARBON İZLENEBİLİRLİĞİ: SÜRDÜRÜLEBİLİR ÜRETİM İÇİN GÜNCEL BİR DEĞERLENDİRME

DIGITAL PRODUCT PASSPORTS AND CARBON TRACEABILITY IN MACHINING: A CONTEMPORARY REVIEW FOR SUSTAINABLE MANUFACTURING

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ÖZET
Sürdürülebilir üretim ve döngüsel ekonomi hedefleri, ürünlerin malzeme içeriği ile üretim ve yaşam döngüsü boyunca meydana gelen çevresel etkilerin güvenilir biçimde izlenmesini gerekli hâle getirmiştir. Dijital Ürün Pasaportu (DÜP), ürün kimliği, malzeme bileşimi, üretim geçmişi, çevresel performans, bakım, yeniden kullanım ve geri dönüşüm bilgilerinin bütünleşik bir dijital yapı içinde paylaşılmasını sağlayan güncel bir yaklaşımdır. Bu çalışmada DÜP yaklaşımının talaşlı imalat süreçlerindeki karbon izlenebilirliği açısından uygulanabilirliği değerlendirilmiş ve bu süreçlere özgü kavramsal bir veri çerçevesi geliştirilmiştir. Konu odaklı literatür incelemesi kapsamında dijital ürün pasaportları, sürdürülebilir talaşlı imalat, enerji tüketimi, kesici takımların ve kesme sıvılarının yaşam döngüsü ile işlem kaynaklı karbon emisyonlarını ele alan 13 çalışma incelenmiştir. Bulgular, talaşlı imalatın karbon ayak izinin yalnızca tezgâh elektriğinden oluşmadığını göstermektedir. Hammadde, kesici takım, kesme sıvısı, işlem süresi, boşta çalışma, talaş oluşumu ve geri kazanım uygulamalarının da hesaba katılması gerektiğini göstermektedir. Bu doğrultuda DÜP için ürün ve malzeme bilgileri, işlem bilgileri, enerji tüketimi, takım ve kesme sıvısı kullanımı, atık ve geri kazanım bilgileri ile karbon göstergelerinden oluşan altı bileşenli bir çerçeve önerilmiştir. Çerçeve, karbon yoğun işlemlerin belirlenmesi ve alternatif üretim stratejilerinin karşılaştırılması için uygulanabilir bir başlangıç sunmaktadır. Veri standardizasyonu, sistemler arası birlikte çalışabilirlik, ticari bilgilerin korunması ve karbon hesabı sınırlarının belirlenmesi temel uygulama güçlükleridir.
Anahtar kelimeler: Dijital ürün pasaportu, talaşlı imalat, karbon izlenebilirliği, sürdürülebilir üretim, döngüsel ekonomi.

ABSTRACT
Sustainable manufacturing and circular economy objectives require reliable traceability of material content and environmental impacts throughout manufacturing and product life cycles. The Digital Product Passport (DPP) is an emerging approach that enables product identification, material composition, manufacturing history, environmental performance, maintenance, reuse and recycling information to be shared within an integrated digital structure. This study evaluates the applicability of DPPs to carbon traceability in machining and develops a conceptual data framework tailored to machining processes. A topic-focused literature review examined 13 studies addressing digital product passports, sustainable machining, energy consumption, the life cycles of cutting tools and cutting fluids, and process-related carbon emissions. The findings show that the carbon footprint of machining is not limited to machine-tool electricity. Raw material, cutting tools, cutting fluids, processing time, idle operation, chip generation and recovery practices should also be considered. Accordingly, a six-component DPP framework is proposed, comprising product and material information, process information, energy consumption, tool and cutting-fluid use, waste and recovery information, and carbon indicators. The framework provides a practical starting point for identifying carbon-intensive operations and comparing alternative manufacturing strategies. Data standardisation, interoperability, protection of commercially sensitive information and the definition of carbon-accounting boundaries remain the main implementation challenges.
Keywords: Digital product passport, machining, carbon traceability, sustainable manufacturing, circular economy.

GİRİŞ

İmalat sanayisi ekonomik değer üretirken enerji ve malzeme tüketimi, sera gazı emisyonları ve atık oluşumu bakımından önemli çevresel etkilere yol açmaktadır. Karbon azaltma hedefleri, üretim işletmelerini yalnızca toplam enerji tüketimini izlemeye değil, bu tüketimin hangi ürün, operasyon ve süreç koşullarından kaynaklandığını belirlemeye yöneltmektedir. Talaşlı imalat bu açıdan dikkat çekici bir alandır. İş parçasından malzeme uzaklaştırılması sırasında tezgâh elektriği, hammadde, kesici takım, kesme sıvısı ve yardımcı sistemler birlikte kullanılmaktadır. İşlem sonunda talaş, kullanılmış akışkan ve aşınmış takım gibi farklı atık akışları oluşmaktadır. Bu nedenle bir parçanın üretim kaynaklı karbon ayak izi tek bir enerji ölçümüyle açıklanamaz (Li vd., 2015; Wang vd., 2023; Wu vd., 2025).

Talaşlı imalatta çevresel performansın iyileştirilmesine yönelik çalışmalar ise enerji modelleme, kesme parametrelerinin optimizasyonu, çevre dostu soğutma ve yağlama stratejileri ile takım ve süreç performansının geliştirilmesi gibi farklı alanlarda yoğunlaşmaktadır (Rajmohan vd., 2020; Wang vd., 2023). Kesme hızı, ilerleme ve kesme derinliği paremetreleri işlem süresini, enerji ve malzeme tüketimini, takım ömrünü ve üretim maliyetini birlikte etkilediğinden karbon emisyonu, maliyet ve işlem süresi hedefleri arasında bir denge kurulması gerekmektedir (Zhou vd., 2019). Benzer şekilde operasyon sırası ve çizelgeleme kararları da boşta çalışma sürelerini ve toplam karbon ayak izini değiştirebilmektedir (Lin vd., 2015). Bununla birlikte bu çalışmaların ürettiği verilerin ürünün kimliğiyle ilişkilendirilmesi ve yaşam döngüsü boyunca erişilebilir tutulması hâlen önemli bir araştırma ve uygulama alanıdır.

Dijital Ürün Pasaportu, ürün tanımlama, ürün ve malzeme özellikleri, kullanım ve bakım, tedarik zinciri ve tersine lojistik, çevresel performans ve mevzuata uygunluk bilgilerinin dijital bir yapı içerisinde saklanmasını ve ilgili tedarik zinciri aktörleri arasında paylaşılmasını amaçlamaktadır. DÜP kapsamında ihtiyaç duyulan veriler, desteklenen karar ve kullanım durumunun yanı sıra veriyi kullanan tedarik zinciri aktörünün rolüne göre farklılaşmaktadır (Jensen vd., 2023). Bu nedenle Dijital Ürün Pasaportu, yalnızca ürüne iliştirilen bir QR kod veya benzeri fiziksel veri taşıyıcısı olarak değerlendirilmemelidir. QR kod, kullanıcıyı ürünün dijital kaydına yönlendiren bir erişim aracı niteliğindedir; DÜP'ün kendisi ise standartlaştırılmış veri tanımları ve modelleri, benzersiz ürün kimliği, farklı paydaşlara göre düzenlenen erişim yetkileri, veri güvenliği ve doğrulama mekanizmaları, sistemler arası birlikte çalışabilirlik ve ürünün tüm yaşam döngüsü boyunca oluşturulan veri akışları üzerine kurulu kapsamlı bir bilgi mimarisidir (Psarommatis ve May, 2024; Wicaksono vd., 2025). Avrupa Birliği'nin 2024/1781 sayılı Sürdürülebilir Ürünler için Eko-Tasarım Tüzüğü de ürün bilgilerinin dijital olarak erişilebilir kılınmasına yönelik hukuki çerçeveyi güçlendirmiştir (European Union, 2024).

Bu çalışmanın amacı, DÜP yaklaşımını talaşlı imalatın karbon kaynaklarıyla ilişkilendirmek ve işlem düzeyinde kullanılabilecek kavramsal bir veri çerçevesi önermektir. Çalışmanın araştırma sorusu "Bir parçanın talaşlı imalat sürecinde oluşan karbon bilgisi, ürün yaşam döngüsü boyunca hangi veri bileşenleriyle izlenebilir?" biçiminde tanımlanmıştır. Çalışmanın özgün katkısı, DÜP literatüründeki ürün ve yaşam döngüsü veri gereksinimleri ile talaşlı imalattaki ölçülebilir çevresel girdileri altı bileşenli ortak bir yapıda eşleştirmesidir.

YÖNTEM

Çalışmada konu odaklı literatür incelemesi yöntemi kullanılmıştır. İnceleme, sistematik derleme veya meta-analiz iddiası taşımamaktadır. Birbirini tamamlayan üç literatür akışını kavramsal olarak sentezlemektedir. Birinci akış DÜP'ün tanımı, veri kümeleri, aktörleri, standardizasyonu ve benimsenme güçlüklerini, ikinci akış sürdürülebilir talaşlı imalatın ekipman, işlem ve strateji boyutlarını, üçüncü akış ise enerji, malzeme, kesici takım, kesme sıvısı ve atık kaynaklı karbon modelleme yaklaşımlarını kapsamaktadır.

İnceleme kümesi, 2013-2025 döneminde yayımlanmış 13 hakemli çalışmadan oluşturulmuştur. Çalışmalar konuya doğrudan katkı sunması, talaşlı imalatın çevresel girdilerinden en az birini ele alması veya DÜP için ürün yaşam döngüsü verilerini tanımlaması ölçütleriyle değerlendirilmiştir. Ayrıca DÜP'ün düzenleyici bağlamını göstermek amacıyla Avrupa Birliği'nin 2024/1781 sayılı Tüzüğü incelenmiştir. Her çalışma amaç, kapsam, veri türü ve önerilen çerçeveye katkısı bakımından kodlanmıştır. Kodlama sonucunda yinelenen veri gereksinimleri altı ana bileşen altında birleştirilmiştir.

Tablo 1. İncelenen literatür akışlarının çalışma çerçevesine katkısı

Literatür akışı	İncelenen konu	Çerçeveye aktarılan veri	Temel kaynaklar
Dijital ürün pasaportu	Yaşam döngüsü kararları, veri kümeleri, erişim ve benimsenme	Ürün kimliği, malzeme bilgisi, çevresel göstergeler, kullanım ve bakım kayıtları, yaşam sonu bilgileri, veri güvenliği ve birlikte çalışabilirlik	Jensen vd. (2023); Psarommatis ve May (2024); Wicaksono vd. (2025)
Sürdürülebilir talaşlı imalat	Tezgâh, işleme süreci, kesici takım, kesme sıvısı ve sürdürülebilir işleme stratejileri	Tezgâh, operasyon, kesme parametreleri, takım kullanımı, soğutma/yağlama koşulları ve süreç optimizasyonu	Wang vd. (2023); Rajmohan vd. (2020)
Karbon modelleme ve optimizasyon	Enerji tüketimi, hammadde, kesici takım, kesme sıvısı, talaş ve süreç optimizasyonu	Tezgâhın boşta ve yükte enerji tüketimi, malzeme ve yardımcı girdi tüketimi, talaş oluşumu, CO_2e ve karbon–süre–maliyet dengesi	Li vd. (2015); Zhou vd. (2019); Wu vd. (2025)
Yaşam döngüsü değerlendirmesi	Kesici takım ve kesme sıvısının üretim, kullanım, bakım/yenileme ve yaşam sonu aşamaları	Fonksiyonel birim, sistem sınırı, takım ömrü, yeniden bileme ve kaplama, kesme sıvısı türü ve miktarı, enerji tüketimi, bertaraf ve geri kazanım	Li vd. (2017); Khanna vd. (2021); Shah vd. (2021)

BULGULAR VE TARTIŞMA

Dijital Ürün Pasaportunun Veri Yapısı

DÜP literatürü, ürün verisinin tek bir paydaşın ihtiyacına göre tanımlanamayacağını göstermektedir. Tedarikçi, üretici, bakım hizmeti sağlayıcısı, müşteri ve geri dönüşüm işletmesi aynı ürüne farklı karar noktalarından yaklaşmaktadır. Üretici malzeme ve süreç bilgisini kullanırken bakım sağlayıcısı kullanım koşulları ile bileşen geçmişine, geri dönüşüm işletmesi ise malzeme ayrıştırma ve tehlikeli içerik bilgisine ihtiyaç duymaktadır. Jensen vd. (2023), bu nedenle DÜP veri gereksinimlerinin yaşam döngüsü kararı ve kullanıcı rolüyle birlikte belirlenmesi gerektiğini göstermiştir. Talaşlı imalat bağlamında bu yaklaşım, tezgâh ve proses verilerinin doğrudan ürüne aktarılmasından önce verinin hangi sürdürülebilirlik kararını desteklediğinin tanımlanmasını gerektirir.

DÜP'ün etkili olabilmesi için veri doğruluğu, güncellik, birlikte çalışabilirlik ve erişim kontrolü birlikte sağlanmalıdır. Üretim parametrelerinin tamamının herkese açık biçimde paylaşılması ticari sır ve fikrî mülkiyet açısından uygun değildir. Buna karşılık karbon yoğunluğu, geri dönüştürülmüş içerik veya yaşam sonu talimatları gibi doğrulanabilir göstergelerin tedarik zinciri boyunca paylaşılması gerekir. Psarommatis ve May (2024), Dijital Ürün Pasaportu'nu ürünün üretim, kullanım ve döngüsellik aşamalarında oluşan verileri bütünleştirerek izlenebilirliği, yaşam döngüsü yönetimini ve sürdürülebilir üretimi destekleyen bir yapı olarak ele almaktadır. Wicaksono vd. (2025) ise DÜP'ün uygulanabilirliğini ve teknik altyapı, veri standardizasyonu, sistemler arası birlikte çalışabilirlik, veri yönetişimi, paydaş katılımı ve benimsenme koşulları çerçevesinde değerlendirmektedir. Bu doğrultuda talaşlı imalata yönelik bir DÜP yapısı, operasyon ve kaynak kullanımına ilişkin ayrıntılı süreç verilerini yaşam döngüsü boyunca korumalıdır. Diğer taraftan paydaşlara rolleri ve kullanım amaçlarıyla sınırlandırılmış, güvenli erişim yetkileri sunmalıdır (Psarommatis ve May, 2024; Wicaksono vd., 2025).

Talaşlı İmalatta Karbon Kaynakları

CNC tabanlı talaşlı imalat sistemlerinde karbon emisyonu beş ana kaynak grubunda ele alınabilir: elektrik, hammadde, kesici takım, kesme sıvısı ile talaş ve diğer atıklar. Elektrik kaynaklı emisyon, aktif

kesme, eksen hareketleri, takım değiştirme, soğutma, basınçlı hava ve boşta çalışma gibi farklı durumlarda tüketilen enerjinin ilgili elektrik emisyon faktörüyle çarpılması yoluyla hesaplanabilir. Ancak toplam etkinin yalnızca tezgâh elektriğine indirgenmesi, malzemenin gömülü karbonunu ve sarf girdilerini görünmez hâle getirir. Li vd. (2015), CNC tabanlı işleme sistemlerinde elektrik tüketimi, hammadde, kesme sıvısı, kesici takım ve talaş yönetiminden kaynaklanan emisyonları birlikte değerlendiren analitik bir nicel yöntem önermiştir. Wu vd. (2025) ise tornalama, frezeleme, delme, taşlama ve dişli azdırma başta olmak üzere farklı imalat süreçleri için geliştirilen karbon emisyonu modellerini sistematik olarak incelemiştir. Kesme parametreleri, takım ve iş parçası özellikleri, enerji tüketimi, kesme sıvısı kullanımı ve atık yönetiminin emisyonlar üzerindeki etkilerini bütüncül biçimde değerlendirmiştir. Hammadde kaynaklı etki, başlangıç kütlesi ile nihai parça kütlesi arasındaki farkın ve malzemeye özgü emisyon faktörünün bilinmesini gerektirir. Uzaklaştırılan talaşın kirlenme düzeyi ve geri kazanım senaryosu bu hesabı değiştirebilir. Ayrı toplanan ve geri dönüştürülen metal talaşı ile kesme sıvısıyla yoğun biçimde kirlenmiş talaş aynı çevresel sonuca sahip değildir. Bu nedenle DÜP kaydı yalnızca talaş miktarını değil, malzeme türünü, kirlenme durumunu, taşıma ve geri kazanım senaryosunu da içermelidir.

Kesme hızı, ilerleme ve kesme derinliği gibi işlem parametreleri enerji ve malzeme tüketimini, işlem süresini, takım ömrünü ve üretim maliyetini birlikte etkileyebilmektedir. Bu nedenle düşük karbonlu talaşlı imalatta tek bir performans göstergesinin iyileştirilmesi yerine çevresel ve ekonomik hedeflerin birlikte değerlendirilmesi gerekmektedir. Zhou vd. (2019), kesme parametrelerini karbon emisyonu, kesme süresi ve kesme maliyeti bakımından eş zamanlı olarak ele alan çok amaçlı bir optimizasyon yaklaşımı geliştirmiştir. Bununla birlikte çevresel performans yalnızca kesme bölgesindeki parametrelere bağlı değildir. işlerin işlenme sırası, hazırlık süreleri, tezgâhların boşta bekleme süreleri ve çizelgeleme kararları da toplam üretim süresini ve karbon ayak izini etkilemektedir. Lin vd. (2015), tornalama süreçleri için işlem parametresi optimizasyonu ile akış tipi üretim çizelgelemesini bütünleştirerek toplam tamamlanma süresi ve karbon ayak izini birlikte en aza indirmeyi amaçlamıştır.

Kesici Takım ve Kesme Sıvısının Yaşam Döngüsü

Kesme sıvıları, takım–iş parçası ara yüzündeki sürtünme ve sıcaklığın kontrol edilmesine katkı sağlayarak takım ömrünü ve işlenmiş yüzey kalitesini iyileştirebilir. Bununla birlikte kesme sıvısının üretimi ve hazırlanması, sisteme iletilmesi için tüketilen enerji, kullanım sırasındaki bakım gereksinimi ve yaşam sonundaki arıtma, bertaraf veya geri kazanım işlemleri ek çevresel ve sağlık etkileri oluşturabilmektedir. Bu nedenle MQL, kriyojenik soğutma, kuru kesme ve geleneksel taşırma soğutma seçenekleri yalnızca kullanılan sıvı miktarına göre değerlendirilmemelidir. Aynı zamanda enerji tüketimi, takım ve yüzey performansı, insan sağlığı ve yaşam döngüsü etkileri birlikte dikkate alınarak karşılaştırılmalıdır. Khanna vd. (2021), taşırma, MQL ve LCO_2 koşullarını işleme performansı, çevresel etki ve insan sağlığı bakımından karşılaştırırken, Shah vd. (2021), taşırma, LCO_2 ve LN_2 koşullarını enerji tüketimi, yüzey kalitesi ve yaşam döngüsü etkileri üzerinden değerlendirmiştir. Ross vd. (2023) ise kuru, MQL, kriyojenik CO_2 ve nano-MQL koşullarında enerji tüketimi ile karbon emisyonlarının önemli ölçüde değişebildiğini göstermiştir. Bu bulgulardan hareketle DÜP içerisinde kesme sıvısının türü ve bileşimi, konsantrasyonu, kullanılan ve yenilenen miktarı, kullanım/değişim süresi, enerji gereksinimi ve yaşam sonu yönetim yöntemi temel kayıt alanları olarak tanımlanabilir.

Önerilen Altı Bileşenli DÜP Çerçevesi

Literatür sentezi sonucunda talaşlı imalat için altı veri bileşeninden oluşan kavramsal DÜP çerçevesi geliştirilmiştir. Çerçeve, çevresel sonucu tek başına saklamak yerine sonucu üreten süreç bağlamını da ürün kaydıyla ilişkilendirmektedir. Böylece farklı tezgâh, parametre ve üretim senaryoları karşılaştırılabilir. Hesaplamanın tekrar edilebilirliği ve doğrulanabilirliği artırılabilir. Önerilen bileşenler ve örnek veri alanları Tablo 2'de sunulmuştur.

Tablo 2. Talaşlı imalat için önerilen Dijital Ürün Pasaportu veri çerçevesi

No	Veri bileşeni	Örnek alanlar	Birim / biçim	İzlenebilirlik amacı
1	Ürün ve malzeme	Parça kimliği, revizyon, alaşım, tedarikçi, başlangıç ve son kütle	Metin, kg	Ürünü ve malzeme kaybını tanımlama
2	İşlem bilgisi	Operasyon, tezgâh, kesme hızı, ilerleme, kesme derinliği, işlem ve bekleme süresi	m/min, mm/dev, mm, dk	Karbon hesabının süreç bağlamını koruma
3	Enerji	Aktif kesme, boşta çalışma ve yardımcı ekipman tüketimi; elektrik emisyon faktörü	kWh, kg CO2e/kWh	Elektrik kaynaklı emisyonu hesaplama
4	Takım ve kesme sıvısı	Takım türü ve ömrü, yenileme; sıvı türü, konsantrasyon, tüketim ve devridaim	dk, adet, L, %	Sarf girdilerini yaşam döngüsüyle ilişkilendirme
5	Atık ve geri kazanım	Talaş miktarı ve kirlenmesi, kullanılmış sıvı, aşınmış takım, taşıma ve geri kazanım senaryosu	kg, L, %, metin	Atık yönetimi ve döngüselliği izleme
6	Karbon göstergeleri	Toplam emisyon, birim emisyon, fonksiyonel birim, sistem sınırı, veri kaynağı ve hesap tarihi	kg CO2e; kg CO2e/parça	Karşılaştırılabilir ve doğrulanabilir sonuç üretme

Birinci bileşen, parçanın ve kullanılan hammaddenin benzersiz biçimde tanımlanmasını sağlar. İkinci ve üçüncü bileşenler, işlemin hangi tezgâhta ve hangi koşullarda gerçekleştirildiğini enerji tüketimiyle birlikte kaydeder. Dördüncü bileşen, geleneksel enerji odaklı hesaplarda çoğu zaman ihmal edilen takım ve akışkan girdilerini görünür kılar. Beşinci bileşen üretim sonrası akışları döngüsel ekonomi kararlarıyla ilişkilendirir. Altıncı bileşen ise tüm girdileri tanımlı bir sistem sınırı ve fonksiyonel birim altında karbon göstergesine dönüştürür. Bu yapı, toplam CO2e değerinin yanı sıra değerin hesaplanmasında kullanılan sınır, emisyon faktörü ve veri tarihini de saklayarak karşılaştırmanın güvenilirliğini artırır.

Beklenen Yararlar ve Uygulama Güçlükleri

Önerilen çerçeve, işletme düzeyinde karbon yoğun operasyonların belirlenmesine ve alternatif üretim planlarının karşılaştırılmasına yardımcı olabilir. Aynı parçanın farklı tezgâhlar, kesme parametreleri veya soğutma stratejileri altında üretilmesi durumunda parça başına karbon göstergesi ortak bir fonksiyonel birim üzerinden karşılaştırılabilir. Malzeme kaybı ve talaş geri kazanımı hakkındaki kayıtlar, geri dönüşüm ve yeniden kullanım kararlarını destekleyebilir. Ürün bazlı izlenebilirlik, kurumsal karbon envanterinin süreç düzeyinde açıklanmasını ve tedarik zincirinde doğrulanabilir çevresel bilgi paylaşımını da kolaylaştırabilir.

Bununla birlikte DÜP'ün ölçeklenmesi için dört temel sorun çözülmelidir. İlk olarak farklı tezgâh, üretim yürütme sistemi ve kurumsal kaynak planlama yazılımlarından gelen veriler ortak bir sözlükte tanımlanmalıdır. İkinci olarak veri kalitesi ve ölçüm sıklığı güvence altına alınmalıdır. Nominal tezgâh gücü ile gerçek zamanlı enerji ölçümü aynı doğruluk düzeyinde değildir. Üçüncü olarak süreç reçeteleri ve maliyet bilgileri gibi ticari açıdan hassas veriler için rol temelli erişim uygulanmalıdır. Son olarak sistem sınırı, elektrik emisyon faktörü, geri dönüşüm kredisi ve fonksiyonel birim seçimi açık biçimde

belirtilmelidir. Aksi hâlde aynı ürün için hesaplanan iki karbon göstergesi görünürde benzer olsa bile gerçekte karşılaştırılabilir olmayabilir.

Bu çalışma kavramsal bir çerçeve sunduğu için gerçek üretim ortamında doğrulama yapılmamıştır. İncelenen yayın sayısının sınırlı olması ve konu odaklı seçimin sistematik derleme protokolüne dayanmaması diğer sınırlılıklardır. Buna rağmen seçilen çalışmalar DÜP, sürdürülebilir talaşlı imalat, karbon modelleme ve yaşam döngüsü değerlendirmesi eksenlerini birlikte kapsamakta pilot uygulama için gerekli asgari veri alanlarının belirlenmesine imkân vermektedir.

SONUÇ

Bu çalışmada Dijital Ürün Pasaportu yaklaşımının talaşlı imalatta karbon izlenebilirliği açısından uygulanabilirliği incelenmiştir. Literatür değerlendirmesi, talaşlı imalatın karbon ayak izinin elektrik tüketiminin ötesinde hammadde, kesici takım, kesme sıvısı, işlem süresi, boşta çalışma ve atık geri kazanımını kapsayan çok kaynaklı bir yapı olduğunu göstermiştir. Bu nedenle ürün pasaportunda yalnızca nihai karbon göstergesinin tutulması yeterli değildir. Sonucu üreten tezgâh, işlem parametreleri, süreler, sarf girdileri, sistem sınırı ve emisyon faktörleri de kaydedilmelidir.

Ürün ve malzeme, işlem, enerji, takım ve kesme sıvısı, atık ve geri kazanım ile karbon göstergelerinden oluşan altı bileşenli çerçeve, bu gereksinimleri ortak bir veri yapısında birleştirmektedir. Çerçeve karbon yoğun operasyonların belirlenmesi, alternatif üretim senaryolarının karşılaştırılması ve geri kazanım kararlarının desteklenmesi için uygulanabilir bir başlangıç sunmaktadır. Gelecek çalışmalarda çerçevenin seçilecek bir parçanın gerçek üretim rotasında pilot olarak uygulanması enerji analizörü, CNC kayıtları ve malzeme akışlarından elde edilen verilerle doğrulanması önerilmektedir. Ayrıca veri alanlarının mevcut DÜP standartlarıyla eşleştirilmesi, erişim yetkilerinin tanımlanması ve farklı karbon hesaplama sınırlarının sonuç üzerindeki etkisinin karşılaştırılması gerekmektedir.

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PERFORMANCE ENHANCEMENTS OF COCONUT FIBER-REINFORCED POLYLACTIC ACID COMPOSITES VIA APPLICATION OF TREATMENTS FOR FIBER SURFACE

HİNDİSTAN CEVİZİ LİFİYLE GÜÇLENDİRİLMİŞ POLİLAKTİK ASİT KOMPOZİTLERİNİN LİF YÜZEYİNE UYGULANAN İŞLEMLER YOLUYLA PERFORMANSININ İYİLEŞTİRİLMESİ

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Abstract
Natural fiber reinforced thermoplastic composites (NFRTC) are attracting more attention due to their environmental benefits and potential for improved material properties. NFRTCs present a sustainable alternative to traditional materials using bio-based polymers and natural fibers. That kind of composites generally have lower strength compared to synthetic fiber composites. However, the addition of natural fillers can improve mechanical properties such as tensile and flexural strength, although they may increase moisture absorption due to surface interactions. Improving surface compatibility between the polymer and natural fiber through surface modification is one of the most critical factors, which affects the properties of natural fiber-filled polymeric composites. In this study, two different surface treatment methods were applied to coconut fiber (Coir) to improve the mechanical properties of polylactic acid (PLA)-based composites reinforced with Coir. Coir surfaces were subjected to alkaline and epoxy-functional silane modifications. Coir surfaces were analyzed by FTIR spectroscopy. For composites with 20 wt% Coir content, PLA and Coir samples were compounded by melt-extrusion, followed by an injection molding process. Mechanical performance, melt-flow, water uptake, viscoelastic and morphological behaviors of the composites were characterized using tensile-impact-hardness tests, melt-flow index measurements, water absorption measurements, dynamic mechanical analysis, and scanning electron microscopy, respectively. Discussions of findings were conducted regarding the comparison of surface-treated and untreated fiber involvement in composite samples. According to research results, the enhancements in the performance and reliability of composites by applying surface treatments contribute to the use of PLA/CF composites in various application fields.
Keywords: Interface Interaction, Coconut Fiber, Polylactic Acid, Natural Fiber Reinforced Thermoplastic Composites, Surface Modification

Özet
Doğal elyaf takviyeli termoplastik kompozitler (DETTK), çevresel faydaları ve malzeme özelliklerinin iyileştirilmesi potansiyeli nedeniyle giderek daha fazla ilgi çekmektedir. DETTK'ler, biyo-polimerler ve doğal lifler kullanarak geleneksel malzemelere sürdürülebilir bir alternatif sunmaktadır. Bu tür kompozitler, sentetik elyaf kompozitlere kıyasla genellikle daha düşük mukavemete sahiptir. Bununla birlikte, doğal katkı maddelerinin eklenmesi, yüzey etkileşimleri nedeniyle nem emilimini artırabilse de, çekme ve eğilme mukavemeti gibi mekanik özellikleri iyileştirebilir. Polimer ve doğal lif arasındaki yüzey uyumluluğunun yüzey modifikasyonu yoluyla iyileştirilmesi, doğal lif dolgulu polimerik kompozitlerin özelliklerini etkileyen en kritik faktörlerden biridir. Bu çalışmada, hindistan cevizi lifi (HCL) ile takviye edilmiş polilaktik asit (PLA) bazlı kompozitlerin mekanik özelliklerini iyileştirmek için HCL'ye iki farklı yüzey işleme yöntemi uygulanmıştır. HCL yüzeyleri alkali ve epoksi-fonksiyonel silan modifikasyonlarına tabi tutulmuştur. HCL yüzeyleri FTIR spektroskopisi ile analiz edilmiştir. %20 CF içeriğine sahip kompozitler için, PLA ve CF numuneleri eriyik ekstrüzyonu ve ardından enjeksiyon kalıplama işlemi ile birleştirilmiştir. Kompozitlerin mekanik performansı, erime akışı, su emme, viskoelastik ve morfolojik davranışları sırasıyla, çekme-darbe sertliği testleri, erime akışı indeksi ölçümleri, su emme ölçümleri, dinamik mekanik analiz ve taramalı elektron mikroskobu kullanılarak

karakterize edilmiştir. Bulguların tartışılması, kompozit numunelerde yüzey işlem görmüş ve işlem görmemiş liflerin karşılaştırılmasıyla ilgili olarak yapılmıştır. Araştırma sonuçlarına göre, yüzey işlemlerinin uygulanmasıyla kompozitlerin performansında ve güvenilirliğinde sağlanan iyileştirmeler, PLA/CF kompozitlerinin çeşitli uygulama alanlarında kullanımına katkıda bulunmaktadır.
Anahtar kelimeler: Ara yüzey Etkileşimi, Hindistan Cevizi Lifi, Polilaktik Asit, Doğal Lif Takviyeli Termoplastik Kompozitler, Yüzey Modifikasyonu

NUMERICAL ANALYSIS OF A COMMERCIAL 10X7E DRONE PROPELLER: VALIDATION AND INVESTIGATION

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ABSTRACT
This study presents a numerical investigation of a commercial 10×7E propeller. A geometry reconstruction workflow is outlined which enables the generation of a three-dimensional blade model starting from publicly available tabulated manufacturer data. The procedure is intended to be repeatable for researchers studying similar commercial propellers. The reconstruction process involved importing tabulated station data, scaling the section profiles according to their corresponding chord length and thickness ratios, and applying spatial translations within a CAD environment. Steady RANS simulations were used to evaluate the aerodynamic performance of the reconstructed reference propeller. The numerical results reproduced the overall trends of the available UIUC experimental data with good agreement near the condition of maximum propulsive efficiency. To quantitatively validate the reconstructed baseline model, performance was analyzed using thrust coefficient (C_T), power coefficient (C_P), and Froude efficiency at two distinct advance ratios (J = 0.35 and J = 0.62). At the higher advance ratio of J = 0.62, the reconstructed model demonstrated excellent alignment with the UIUC data, predicting a C_T of 0.0397, a C_P of 0.0346, and an efficiency of 0.707 against the UIUC reference values of 0.0400, 0.0350, and 0.701, respectively. At the lower advance ratio of J = 0.35, the numerical model predicted a C_T of 0.0803, a C_P of 0.0502, and an efficiency of 0.564, compared to the UIUC baseline values of 0.0910, 0.0534, and 0.597. These results confirm that standardizing the airfoil coordinate datasets yields a reliable geometric baseline for further aerodynamic evaluations, particularly under high-efficiency operating conditions.
Keywords: Drone, propeller, RANS simulation

1. INTRODUCTION
Small electric propellers operating at low Reynolds numbers serve as the primary propulsion mechanisms for multirotor drones and small unmanned aerial vehicles (UAVs). The aerodynamic performance of these propulsion systems is highly dependent on complex blade geometry, rotational kinematics, and transitional boundary-layer behavior.
The primary objective of this study is to perform a detailed geometric reconstruction of the commercially available APC 10×7E propeller using open-source manufacturer data (APC Propellers, 2026), and to rigorously validate the aerodynamic performance of this baseline model through computational fluid dynamics approaches. By employing steady RANS simulations coupled with advanced transition modeling, this research resolves the boundary-layer behavior and compares the numerical outcomes with established experimental datasets, thereby establishing a reliable methodology for evaluating off-the-shelf propeller aerodynamics.

2. METHODOLOGY

2.1. Blade geometry reconstruction
The propeller selected for this investigation is the APC Thin Electric 10×7E, a widely utilized off-the-shelf rotor designed for electrically driven UAV applications. The propeller features a hub diameter of 0.80 inches, an overall diameter of 10 inches, and a pitch of 7 inches. In the absence of a native CAD file, the blade geometry was reconstructed using tabulated data provided by the manufacturer. This dataset includes chord length, thickness ratio, twist angle, and z-high values distributed across 36 radial stations extending from the hub to the blade tip.

The aerodynamic profile changes along the blade. An Eppler 63 airfoil is used from the root to a 0.73R radial location, while the rest of the blade uses an APC12 section (which the manufacturer declares as equivalent to NACA 4412). Due to the exact APC12 profile not being public, the NACA 4412 model is used instead. However, this creates uncertainty in the shape and aerodynamic results, which is common in commercial propeller studies (Alves, 2014; Jdiobe, Rouser, Paul, & Rouser, 2022; Lowe, 2009). The reconstruction process was initiated by importing the tabulated station data into the XFLR5 (Deperrois, 2013) environment, where each section profile was appropriately scaled. Subsequently, the scaled airfoils were exported to the Siemens NX CAD software. Through precise translation and rotation operations regarding the designated *x*/*c* locations, a lofting procedure was executed to generate the final 3D solid body. Visual inspection against the physical product confirmed an excellent geometric agreement, with only negligible deviations observed near the complex hub to blade transition region.

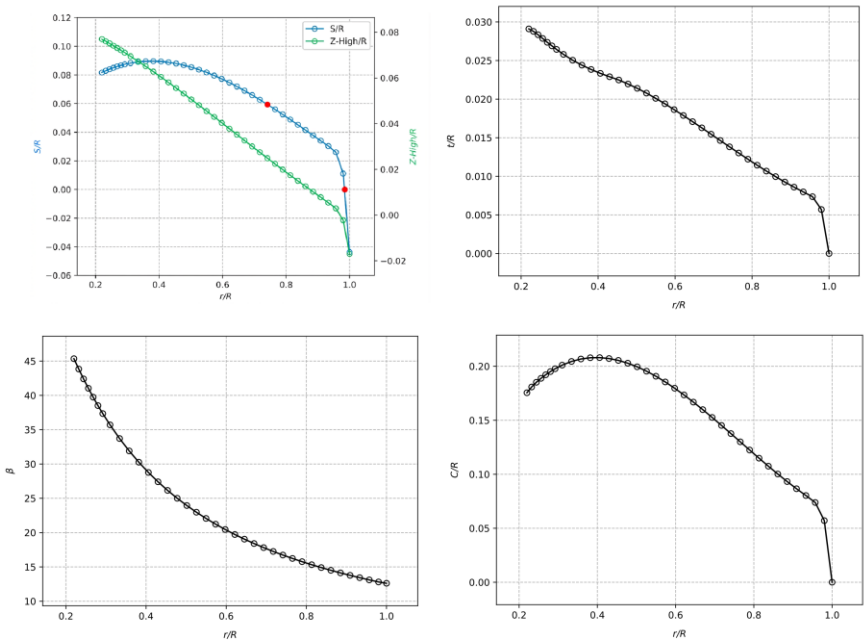


Figure 2 Radial distributions of blade geometric parameters: (a) sweep and *z*-high, (b) thickness, (c) twist angle and (d) chord, Data taken from APC Propellers (2026).



(a) APC 10×7E reconstruction, top view.

(b) APC 10×7E reconstruction, side view.

Figure 3 Superimposed views of the reconstructed 10×7E and the original APC 10×7E

2.2. Numerical model and simulation details

The aerodynamic performance of the propeller is quantified using standard dimensionless parameters. The advance ratio is defined as

$$J = \frac{V_\infty}{nD}, \tag{1}$$

where V_∞ is the free-stream velocity, n is the rotational speed in revolutions per second, and D is the propeller diameter. The thrust and power coefficients are defined as

$$C_T = \frac{T}{\rho n^2 D^4} \text{ and } C_P = \frac{P}{\rho n^3 D^5}, \tag{2}$$

respectively, while the propulsive efficiency is calculated as

$$\eta = \frac{JC_T}{C_P}. \quad (3)$$

A representative Reynolds number is defined at the 0.75R blade section as

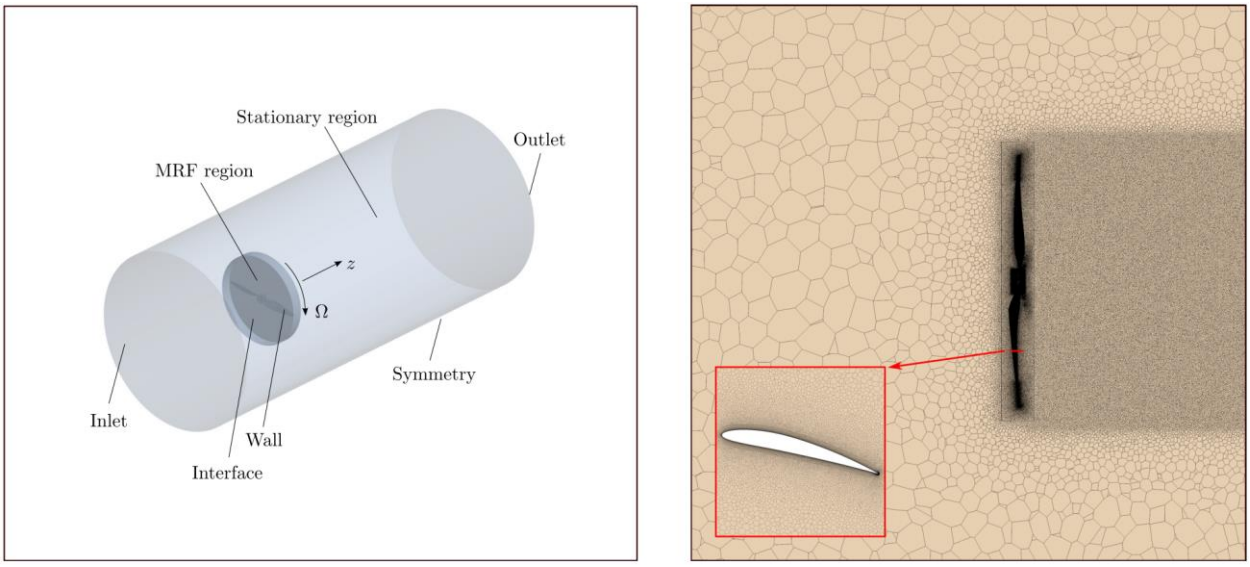
$$Re_{0.75} = \frac{\rho V_\infty c}{\mu}, \quad (4)$$

where the local relative velocity $V_{Rel} = \sqrt{V_\infty^2 + (2\pi nr)^2}$ and the local chord c are evaluated at $0.75R$. The dynamic viscosity is denoted by μ.

The computational fluid dynamics analyses were conducted utilizing Siemens Simcenter STAR-CCM+. A steady Moving Reference Frame (MRF) approach was adopted to model the rotational motion, as this method provides reliable predictions of mean thrust and torque at a practical computational cost (Baltazar, Rijpkema, & Falcão de Campos, 2019; Garofano-Soldado, Sanchez-Cuevas, Heredia, & Ollero, 2022; Zhang, Xie, Wang, & An, 2023). The computational domain was constructed as a cylinder with a diameter of $2.2D$, extending $1.5D$ upstream and $3.5D$ downstream from the propeller plane.

To resolve the complex geometric features and ensure accurate gradient calculations, a polyhedral (Jasak, 1996; Wang, Cao, & Okaze, 2021) mesh comprising approximately 9.24×10^6 cells was utilized. Specifically, a 10-layer prism mesh with a total thickness of 0.25 mm and a first-layer height of 0.01 mm was applied to all blade surfaces, maintaining an average dimensionless wall distance of $y^+ \approx 0.64$.

Flow calculations were performed using the finite volume method and the SIMPLE algorithm, a standard method for linking pressure and velocity in incompressible flows (Ferziger, Perić, & Street, 2020). Turbulence was modeled via the Menter SST $k-\omega$, and to accurately account for laminar to turbulent transition phenomena at low Reynolds numbers ($Re_{0.75} \approx 7.2 \times 10^4$), a γ-based transition model was integrated into the solver.



(a) (b)

Figure 4 Views of the numerical setup: (a) Problem domain and boundary conditions, (b) The polyhedral grid.

3. RESULTS AND DISCUSSION

The fidelity of the RANS modeling approach was verified by comparing the predicted aerodynamic coefficients against the APC manufacturer database and independent wind-tunnel measurements from the UIUC. The advance ratio was swept from $J = 0.18$ to $J = 0.85$ while maintaining a constant rotational speed of 6000 RPM.

At the design condition corresponding to maximum propulsive efficiency $J \approx 0.62$, the numerically predicted thrust coefficient, power coefficient, and propulsive efficiency demonstrated excellent alignment with the UIUC experimental measurements. This indicates that the numerical method accurately captures the governing aerodynamic physics when the blade sections are optimally aligned with the incoming flow. At lower advance ratios, a minor deviation between the calculated thrust values and the experimental data was observed. These differences are mainly caused by complex three-dimensional flow effects, such as increased angles of attack and strong secondary flow effects near the hub, which standard steady RANS models struggle to capture under heavily loaded, off-design conditions. Nonetheless, the calculated power coefficient (C_P) successfully captured the plateauing behavior observed in the experimental data at low advance ratios, confirming the overall reliability of the computational setup.

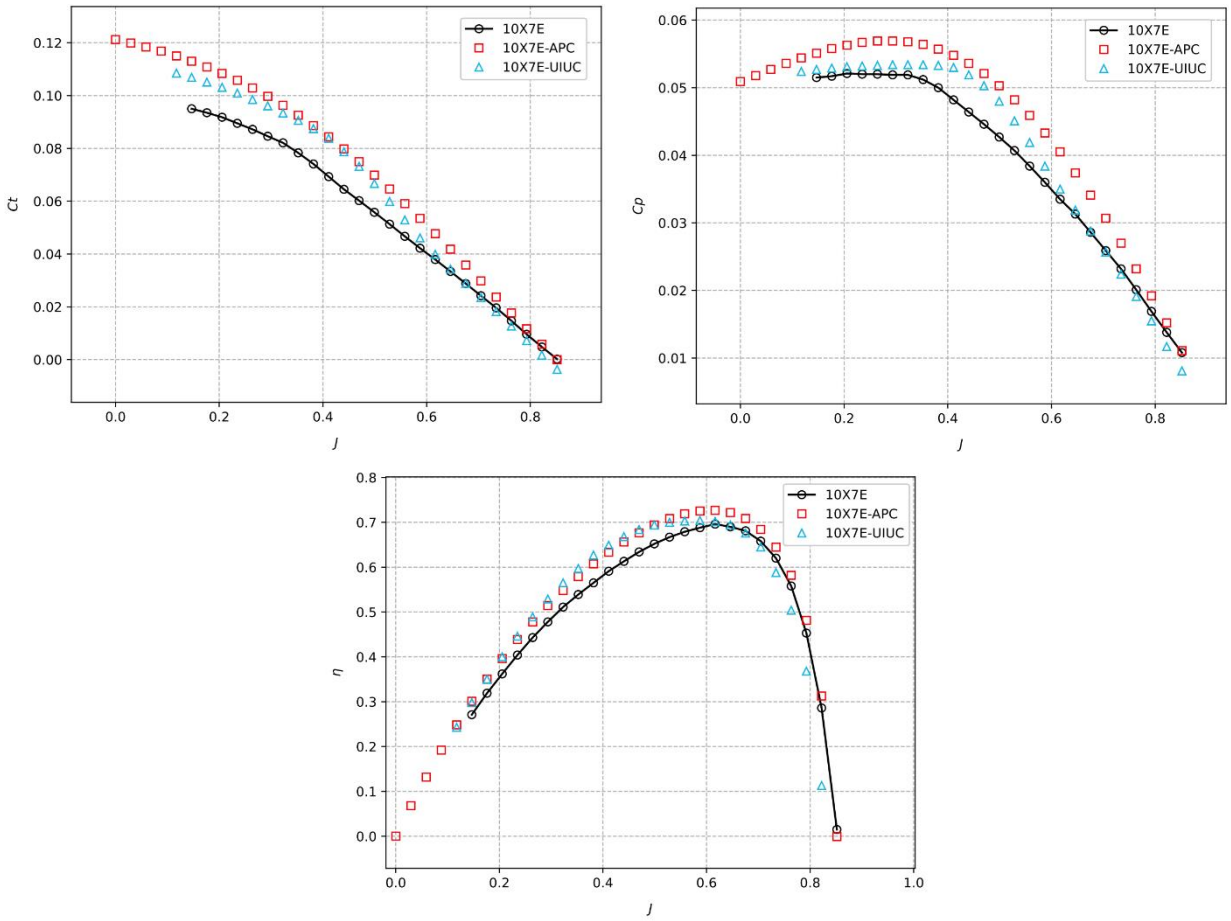


Figure 5 Comparison of propeller performance obtained from RANS simulations (black), UIUC wind-tunnel experiments (blue, Brandt (2008)), and APC database results (red, APC Propellers (2026)) for validation.

4. CONCLUSION

This research demonstrated a robust, repeatable geometry reconstruction workflow for the commercial APC 10×7E drone propeller, utilizing solely publicly available tabulated manufacturer data. This methodology provides a foundation for researchers seeking to perform high-fidelity CFD analyses on commercial propulsion systems lacking native CAD documentation.

The steady RANS computational model predicted the overall aerodynamic behavior of the reconstructed blade. To quantitatively validate the baseline model, performance metrics were evaluated against independent UIUC wind tunnel experimental data (Brandt, 2008; Selig, 2015) at two distinct advance ratios. At the higher advance ratio of J = 0.62, corresponding to peak propulsive efficiency, the numerical model demonstrated excellent alignment, predicting a thrust coefficient (C_T) of 0.0397, a power coefficient (C_P) of 0.0346, and an efficiency (η) of 0.707. These results closely matched the UIUC reference values of 0.0400, 0.0350, and 0.701, respectively. Lower advance ratio of J = 0.35, the model predicted a C_T of 0.0803, a C_P of 0.0502, and an efficiency of 0.564, compared to the UIUC measurements of 0.0910, 0.0534, and 0.597. While minor deviations were observed at this lower advance ratio due to pronounced three-dimensional rotational effects, these quantitative results confirm that standardizing the airfoil coordinate datasets yields a reliable geometric baseline for further aerodynamic evaluations, particularly under high-efficiency operating conditions.

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THE PARADIGM SHIFT IN QUALITY ASSURANCE IN INDONESIAN HIGHER EDUCATION: AN ANALYSIS OF THE LEGAL GAPS IN THE TRANSITION TO MINISTERIAL REGULATION NO. 39 OF 2025 AND STRATEGIES FOR IMPLEMENTING QUALITY ASSURANCE

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ABSTRACT
The implementation of higher education quality assurance in Indonesia is currently facing a fundamental shift following the enactment of the Regulation of the Minister of Higher Education, Science, and Technology (Permendiktisaintek) Number 39 of 2025. This regulation replaces the previous framework, Permendikbudristek Number 53 of 2023, which aimed at simplifying national standards. This research aims to analyze the legal gaps arising from the rapid transition between these two regulations and the institutional readiness of universities to adapt to the new "Global Quality" orientation. Using a normative-conceptual approach, this study identifies a significant gap between the normative requirement for universities to exceed National Higher Education Standards (SN Dikti) and the empirical reality of administrative and financial constraints, particularly for private higher education institutions. The analysis highlights three main issues: the legal consequences of the two-year transition period, the problematic funding and independence of Independent Accreditation Agencies (LAM), and the challenges of integrating data with the Higher Education Database (PD Dikti). The findings suggest that while the new regulation provides greater flexibility, it requires a robust internal quality culture and a realistic roadmap for digital infrastructure to bridge the gap between compliance and excellence.
Keywords: Quality Development; Legal Gap; Accreditation; SN Dikti; Higher Education.

A LEGAL REVIEW OF UNDERAGE MARRIAGES AND DIVORCES AT THE CLASS IA RELIGIOUS COURT IN SAMARINDA

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ABSTRACT
Underage marriage is not something new in Indonesia. This practice has long been the case with so many actors. Not only in big cities but in the hinterland is also a lot going on. The causes vary due to economic problems, lack of education, cultural understanding and the values of a particular religion and the most common problems is pregnant outside marriage (accident or popular with the term married by accident) and other reasons. Usually marriages under age not given birth family happiness and households, thus many lead to divorce and other impacts.
This study using literature data and the data obtained directly from the community as well as information from relevant agencies. A research technique used is the technique of interviewing on interviewees of Religious Court Samarinda Class IA. Methods of analysis of data from this study, using a qualitative analysis, then presented descriptively. The research objective to be achieved include: (1) To gain an understanding that underage marriage should not happen; (2) To determine and analyze the sanctions against breaches of the underage marriage; (3) To know and analyze the impact of underage marriage, particularly divorce. Research conclusion that: (1) The bad impact of underage marriage is increasing maternal mortality and especially the impact of divorce that rise in Indonesia and Samarinda in particular. (2) The sanctions law imposed on anyone who violates the provisions of the law of marriage and child protection laws. Judging from the law that marriage is legalized by the procedures and requirements of the religion that believed the nature of the marriage is valid.
Keywords: underage marriage, Religious Caourt, protection, divorce

CRIMINAL LIABILITY OF PUBLIC OFFICIALS IN THE ISSUANCE OF CONSTRUCTION PERMITS IN THE REPUBLIC OF MOLDOVA: ABUSE OF OFFICE, NEGLIGENCE AND THE IMPACT OF ADMINISTRATIVE DECISIONS

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ABSTRACT

The issuance of construction permits represents an essential administrative function through which public authorities ensure compliance with urban planning, construction, environmental, safety, and property protection requirements. In the Republic of Moldova, the increasing complexity of construction activities and administrative procedures creates significant risks associated with unlawful decision-making, abuse of office, negligence, and insufficient institutional control. This article examines the criminal liability of public officials involved in the issuance of construction permits, with particular emphasis on abuse of office and negligence in office under the Criminal Code of the Republic of Moldova. The research analyses the relationship between administrative unlawfulness and criminal liability, emphasizing that the mere annulment or illegality of an administrative decision does not automatically constitute a criminal offence. Particular attention is given to the provisions of the Urbanism and Construction Code No. 434/2023, which establishes requirements for the issuance of construction permits and defines the responsibilities of public authorities and officials involved in the permitting process. The study examines the legal criteria for distinguishing intentional abuse of office from negligent performance of official duties, including the mental element, the existence of legally relevant damage, and the causal relationship between the official's conduct and the resulting consequences. The research demonstrates that unlawful construction permits may generate significant risks for property rights, public safety, urban development, and environmental protection. The article argues that effective prevention of such offences requires increased administrative transparency, digitalisation of permitting procedures, institutional supervision, professional verification, and clear individualisation of responsibility. A balanced approach is necessary to ensure accountability while preventing the unjustified criminalisation of bona fide administrative decision-making.

Keywords: construction permits, public officials, criminal liability, abuse of office, negligence in office.

INTRODUCTION

Construction activity is closely connected with the public interest because decisions concerning the location, design, construction and use of buildings may directly affect property rights, public safety, environmental protection, urban development and the quality of life of communities. Consequently, the state establishes a system of administrative authorisation intended to prevent unlawful or unsafe construction and to ensure compliance with planning and technical requirements.

In the Republic of Moldova, the legal framework governing construction permits has undergone substantial development. The current regulatory framework is centred on the Urbanism and Construction Code No. 434/2023, which regulates urban planning, construction permitting, the execution and reception of construction works, quality control and state supervision. The Code contains a dedicated title concerning construction and demolition permits and expressly regulates the obligations and responsibilities of issuers (Parliament of the Republic of Moldova, 2023).

The construction permit is not merely a formal administrative document. It constitutes an important legal instrument through which the competent authority verifies whether the proposed construction satisfies statutory requirements. Under Article 148 of the Urbanism and Construction Code, the construction permit is issued within the prescribed procedure and on the basis of specified documentation, including project documentation and, where applicable, environmental, cultural heritage, infrastructure and other approvals. The issuer must refuse the permit where the documentation contains falsified or erroneous information or where the project does not comply with urban planning requirements (Parliament of the Republic of Moldova, 2023).

This regulatory responsibility raises an important question: under what circumstances does an unlawful administrative decision become a criminal offence committed by the public official responsible for issuing, approving or signing the construction permit?

The answer cannot be reduced to the existence of an unlawful permit. Administrative unlawfulness and criminal unlawfulness are related but distinct legal categories. A permit may be annulled by an administrative authority or court without necessarily establishing the criminal liability of the official who issued it. Criminal liability requires the fulfilment of the legal elements of a specific offence.

This distinction is particularly important in relation to Articles 327 and 329 of the Criminal Code of the Republic of Moldova, which regulate abuse of power or abuse of office and negligence in office, respectively (Parliament of the Republic of Moldova, 2002).

This distinction is particularly important in relation to Articles 327 and 329 of the Criminal Code of the Republic of Moldova, which regulate abuse of power or abuse of office and negligence in office, respectively (Parliament of the Republic of Moldova, 2002).

1.1.INDIVIUDAL RESPONSIBILITY OF THE ISSUING OFFICIAL

One of the most important innovations of the current Moldovan construction legislation is the express regulation of the responsibility of persons involved in the issuance of construction permits.

Article 159 of the Urbanism and Construction Code of the Republic of Moldova establishes specific obligations of the issuer. These include the use of SIA GEAP, ensuring that the preparation of the permit takes place without the applicant's involvement, registration and transmission of information concerning issued permits to the central database of the Register of Permissive Acts, as well as ensuring public access to relevant information (Parliament of the Republic of Moldova, 2023).

Article 161 goes further by providing that responsibility for the correctness of the issuance of construction and demolition permits rests jointly with the persons who signed them.

This provision is particularly relevant from the perspective of criminal law because the issuance procedure may involve several officials. The mayor, local council secretary, chief architect or other authorised persons may participate in signing the permit, depending on the category of project and administrative structure. The current Code expressly regulates who signs the permit in different circumstances.

However, joint administrative responsibility should not automatically be equated with joint criminal responsibility.

1. Criminal liability remains personal. Each official must be assessed according to his or her own conduct, competence, knowledge, duties, contribution to the decision-making process and mental attitude toward the violation.
2. Therefore, in criminal proceedings it is necessary to establish:
3. the exact legal and professional duties of the official;
4. whether the official had actual competence in the relevant procedure;
5. which documents were available to the official;
6. whether the violation was objectively detectable;
7. whether the official personally signed, approved, endorsed or otherwise contributed to the unlawful decision;
8. whether the official acted intentionally or negligently;
9. whether legally relevant damage resulted from the conduct; and
10. whether a causal relationship exists between the official's conduct and the damage.

This approach prevents the criminalisation of officials merely because they participated formally in an administrative procedure.

1.2.ABUSE OF OFFICE IN THE ISSUANCE OF CONSTRUCTION

Article 327 of the Criminal Code of the Republic of Moldova regulates abuse of power or abuse of office. The current formulation criminalises intentional performance or non-performance, in the exercise of official duties, of an action in violation of the law, when committed for a material interest, another personal interest or the interest of a third person and resulting in considerable damage to legally protected rights and interests (Parliament of the Republic of Moldova, 2002).

The offence therefore contains several essential components:

a) a public official as the perpetrator;

b) conduct occurring in the exercise of official duties;
c) violation of legal requirements;
d) intentional conduct;
e) a material, personal or third-party interest;
f) legally relevant damage; and
g) causal connection between the unlawful conduct and the damage.

In the context of construction permits, abuse of office may potentially arise where an official knowingly issues a permit despite the absence of mandatory documents, knowingly disregards a statutory prohibition, intentionally approves a project that does not satisfy urban planning requirements, or deliberately facilitates the interests of a particular developer. However, the existence of an unlawful permit alone does not prove abuse of office. The prosecution must establish the official's intentional violation of the law and the legally required interest motivating the conduct.

1.3.TYPICAL FORMS OF ABUSIVE CONDUCT

From a criminal-law perspective, the issuance of construction permits represents an area in which the exercise of public authority may generate significant legal consequences when statutory requirements are deliberately disregarded. Public officials involved in the permitting process are entrusted with the responsibility of verifying whether the proposed construction complies with applicable urban planning, technical, environmental, safety, property, and administrative requirements. Consequently, the intentional misuse of official powers in this field may, depending on the circumstances and the evidence available, fall within the scope of abuse of office as regulated by Article 327 of the Criminal Code of the Republic of Moldova (Parliament of the Republic of Moldova, 2002).

A first hypothetical situation concerns the intentional issuance of a construction permit despite the official's knowledge that mandatory approvals or supporting documents are missing. In the ordinary permitting procedure, the official has a duty to verify whether the application is accompanied by the documentation required by law. If the official is aware that a mandatory approval has not been obtained, but nevertheless deliberately proceeds with the issuance of the permit, the conduct may represent more than a simple administrative error. The criminal-law assessment would depend, in particular, on establishing that the official knew about the missing documentation, possessed the legal competence to refuse or suspend the procedure, and nevertheless intentionally decided to issue the permit. Where the conduct is additionally motivated by a material, personal, or third-party interest and produces the legally required damage, the elements of abuse of office may potentially be established.

A second situation may arise where an official knowingly authorises construction in breach of mandatory urban planning restrictions in order to favour a particular private developer. Urban planning restrictions are designed to protect the public interest and to ensure the coherent development of settlements. They may concern land-use regulations, construction parameters, protected areas, height restrictions, building density, distances from neighbouring properties, infrastructure requirements, or other mandatory planning conditions. If an official is fully aware that a proposed project contradicts binding planning rules but intentionally approves the project because of a relationship with, or an interest in benefiting, a particular developer, the administrative decision may acquire a clear criminal-law dimension. In such circumstances, the investigation would need to establish not only the unlawfulness of the permit but also the official's knowledge of the applicable restrictions, the intentional nature of the decision, the existence of the relevant personal or third-party interest, and the resulting damage.

A third hypothetical situation concerns the deliberate disregard of falsified, incomplete, or manifestly erroneous documents submitted by the applicant. The permitting authority is expected to assess the formal and legal validity of the documentation submitted in support of the application. Where an official is made aware that documents contain false information or significant inconsistencies, but consciously ignores those deficiencies and issues the permit, the official's conduct may potentially constitute an abuse of official powers. This situation is particularly relevant where the false documentation concerns essential aspects of the project, such as ownership rights, land-use conditions, technical parameters, structural characteristics, environmental approvals, or compliance with urban planning documentation. Nevertheless, the mere existence of an incorrect document is insufficient to establish criminal liability. It must be demonstrated that the official knew, or was otherwise consciously aware, of the relevant irregularity and deliberately chose to disregard it.

A fourth situation involves the manipulation of the administrative permitting procedure in order to circumvent statutory requirements or accelerate the issuance of a construction permit for a favoured applicant. Such manipulation may take different forms, including bypassing mandatory procedural stages, improperly reducing verification periods, preventing other competent institutions from providing required opinions, altering the sequence of administrative actions, or deliberately avoiding checks that could reveal deficiencies in the application. From a criminal-law perspective, the essential issue is whether the official intentionally used his or her position and institutional powers to defeat the purpose of the statutory procedure. Where such conduct is directed toward obtaining an unlawful advantage for a particular applicant and causes legally relevant damage, it may warrant investigation under the provisions concerning abuse of office.

A fifth situation may arise where an official knowingly signs or endorses a construction permit despite the existence of a previous administrative or technical finding demonstrating that the proposed project does not satisfy applicable legal or technical requirements. Such circumstances are particularly significant because a prior technical report, inspection finding, administrative refusal, or expert assessment may provide objective evidence that the official was aware of the project's deficiencies. If, despite this information, the official deliberately signs the permit, the evidentiary significance of the prior finding may be considerable in determining the official's knowledge and intent. The investigation should nevertheless establish whether the official had access to the relevant finding, whether it fell within the official's sphere of responsibility, and whether the official had the legal authority to prevent the issuance of the permit.

These hypothetical situations demonstrate that the criminal-law assessment of unlawful construction permits cannot be based exclusively on the final administrative outcome. The fact that a construction permit is subsequently annulled, declared unlawful, or found to have been issued contrary to urban planning legislation does not, by itself, establish the criminal liability of the official who participated in its issuance. Criminal liability requires an individualised examination of the conduct of each person involved in the administrative process.

Particular importance must therefore be attributed to the subjective element of the offence. In cases involving abuse of office, investigators must establish whether the official acted intentionally and whether the conduct was associated with the material, personal, or third-party interest required by the criminal-law provision. This requires an examination of the circumstances existing at the moment the administrative decision was adopted, rather than relying solely on the harmful consequences that subsequently occurred.

Evidence may include the content of the administrative file, internal correspondence, electronic records, entries in digital permitting systems, technical opinions, inspection reports, communications between officials and applicants, financial information, and other circumstances capable of demonstrating the official's knowledge and purpose. The digitalisation of construction-permitting procedures may be particularly important because electronic records can make it possible to reconstruct the chronology of the decision-making process and identify the persons who prepared, verified, approved, modified, or signed relevant documents.

Accordingly, the criminal investigation should distinguish between an objective violation of construction legislation and an intentional misuse of official authority. The first may justify administrative, disciplinary, or contraventional consequences, whereas the second, when accompanied by all legally required elements, may give rise to criminal liability.

The central principle should therefore be that an unlawful construction permit is not automatically equivalent to abuse of office. Criminal responsibility can arise only where the prosecution establishes, beyond the mere existence of an administrative irregularity, the specific conduct of the official, the violation of the applicable legal duty, the required mental element, the legally relevant interest or purpose, the existence of legally significant damage, and the causal relationship between the official's conduct and the resulting consequences. This approach ensures both effective protection of the public interest and respect for the principle of legality and the individualisation of criminal responsibility.

1.4.INDIVIDUAL RESPONSIBILITY OF THE ISSUING OFFICIAL

One of the most important innovations of the current Moldovan construction legislation is the express regulation of the responsibility of persons involved in the issuance of construction permits.

Article 159 of the Urbanism and Construction Code establishes specific obligations of the issuer. These include the use of SIA GEAP, ensuring that the preparation of the permit takes place without the applicant's involvement, registration and transmission of information concerning issued permits to the central database of the Register of Permissive Acts, as well as ensuring public access to relevant information (Parliament of the Republic of Moldova, 2023).

Article 161 goes further by providing that responsibility for the correctness of the issuance of construction and demolition permits rests jointly with the persons who signed them.

This provision is particularly relevant from the perspective of criminal law because the issuance procedure may involve several officials. The mayor, local council secretary, chief architect or other authorised persons may participate in signing the permit, depending on the category of project and administrative structure. The current Code expressly regulates who signs the permit in different circumstances.

However, joint administrative responsibility should not automatically be equated with joint criminal responsibility.

Criminal liability remains personal. Each official must be assessed according to his or her own conduct, competence, knowledge, duties, contribution to the decision-making process and mental attitude toward the violation.

Therefore, in criminal proceedings it is necessary to establish:

1. the exact legal and professional duties of the official;
2. whether the official had actual competence in the relevant procedure;
3. which documents were available to the official;
4. whether the violation was objectively detectable;
5. whether the official personally signed, approved, endorsed or otherwise contributed to the unlawful decision;
6. whether the official acted intentionally or negligently;
7. whether legally relevant damage resulted from the conduct; and
8. whether a causal relationship exists between the official's conduct and the damage.

This approach prevents the criminalisation of officials merely because they participated formally in an administrative procedure.

1.5.ABUSE OF OFFICE IN THE ISSUANCE OF CONSTRUCTION PERMITS

Article 327 of the Criminal Code of the Republic of Moldova regulates abuse of power or abuse of office. The current formulation criminalises intentional performance or non-performance, in the exercise of official duties, of an action in violation of the law, when committed for a material interest, another personal interest or the interest of a third person and resulting in considerable damage to legally protected rights and interests (Parliament of the Republic of Moldova, 2002).

The offence therefore contains several essential components:

1. a public official as the perpetrator;
2. conduct occurring in the exercise of official duties;
3. violation of legal requirements;
4. intentional conduct;
5. a material, personal or third-party interest;
6. legally relevant damage; and
7. causal connection between the unlawful conduct and the damage.

In the context of construction permits, abuse of office may potentially arise where an official knowingly issues a permit despite the absence of mandatory documents, knowingly disregards a statutory prohibition, intentionally approves a project that does not satisfy urban planning requirements, or deliberately facilitates the interests of a particular developer.

However, the existence of an unlawful permit alone does not prove abuse of office. The prosecution must establish the official's intentional violation of the law and the legally required interest motivating the conduct.

From a criminal-law perspective, several hypothetical situations may illustrate the potential application of Article 327.

First, an official may intentionally issue a construction permit despite knowing that the project documentation lacks mandatory approvals.

Second, an official may knowingly approve construction in violation of binding urban planning restrictions in order to benefit a particular private developer.
Third, an official may intentionally ignore falsified or manifestly erroneous documents submitted by the applicant.
Fourth, an official may manipulate the administrative procedure in order to circumvent statutory requirements and accelerate the issuance of a permit for a favoured applicant.
Fifth, an official may knowingly sign a permit despite a prior administrative or technical finding that the proposed project does not comply with applicable requirements.
In each situation, however, criminal liability depends upon evidence establishing the specific elements of the offence.
The second major form of potential criminal liability is negligence in office.
Article 329 of the Criminal Code of the Republic of Moldova provides liability for failure to perform or improper performance by a public official of statutory official duties resulting from a negligent or unconscientious attitude, where this causes damage of a legally significant degree to protected rights and interests. The aggravated forms concern, among other circumstances, persons holding public dignity positions or particularly serious damage (Parliament of the Republic of Moldova, 2002).
The fundamental distinction between Article 327 and Article 329 is therefore the mental element.
Abuse of office requires intentional conduct combined with the legally specified interest. Negligence, by contrast, concerns improper performance or failure to perform official duties resulting from a negligent or unconscientious attitude.
This distinction is particularly important in the construction sector because permitting procedures frequently involve highly technical documentation.
An official may be confronted with architectural plans, structural calculations, environmental assessments, technical reports, property documents and multiple administrative approvals. The official cannot necessarily be expected to possess the specialised knowledge of an architect, engineer or technical expert.
Consequently, criminal negligence should not be established merely because a technical defect existed in the documentation.
The investigation must determine whether the official had a legal duty to identify the defect, whether the defect was reasonably identifiable within the official's competence and whether the failure to act represented a legally relevant departure from the standard expected from the official.

1.6.DISTINGUISHING ABUSE FROM NEGLIGENCE

The distinction between abuse of office and negligence in office is of particular importance when examining the criminal liability of public officials involved in the issuance of construction permits in the Republic of Moldova. Although both offences may involve a violation or improper performance of official duties and may produce legally significant damage, they differ fundamentally with regard to the mental element, the nature of the official's conduct, and the evidentiary requirements necessary to establish criminal responsibility.
The most important distinction concerns the mental element. Abuse of office presupposes intentional conduct. The official consciously performs an action or deliberately fails to perform an action that falls within his or her official duties, while being aware of the unlawfulness of that conduct. In contrast, negligence in office is characterised by a negligent or unconscientious attitude toward the performance of official duties. The official does not necessarily intend the harmful consequence or the violation itself but fails to exercise the degree of care, attention, and diligence required by the position.
This distinction becomes particularly relevant in construction permitting procedures, which frequently involve complex technical and legal documentation. An official who knowingly issues a construction permit despite being aware that mandatory requirements have not been fulfilled may potentially act intentionally. By contrast, an official who fails to identify an irregularity because the documentation was not adequately examined, although the official was under a legal duty to conduct such verification, may potentially fall within the sphere of negligence, provided that all statutory elements of the offence are established.
A second important distinction concerns the nature of the conduct. Abuse of office involves the deliberate misuse of the powers or responsibilities associated with public office. The official may use a legally conferred authority for an unlawful purpose or deliberately refrain from exercising that authority

in order to facilitate a particular outcome. In the construction sector, this could include knowingly authorising a project that does not comply with mandatory urban planning requirements, deliberately disregarding an obvious legal prohibition, or intentionally circumventing a prescribed verification procedure.

Negligence in office, by comparison, generally results from the inadequate performance or non-performance of official duties rather than from a deliberate attempt to misuse public authority. For example, an official may fail to verify whether all mandatory documents have been submitted, overlook a significant inconsistency in the administrative file, or improperly perform a verification procedure. The critical question is whether such conduct reflects a legally relevant failure of diligence rather than an intentional decision to violate the law.

Another important criterion is the existence of a material, personal, or third-party interest. In the case of abuse of office under Article 327 of the Criminal Code of the Republic of Moldova, the relevant statutory conditions concerning the interest motivating the conduct must be established. This element is particularly significant where an official deliberately facilitates the interests of a private developer, construction company, intermediary, relative, associate, or another beneficiary. Evidence concerning financial relationships, communications, conflicts of interest, previous interactions, or other circumstances may therefore become relevant to determining the purpose behind the official's conduct.

In negligence cases, such a personal or third-party interest is not the defining feature of the offence. The central issue is instead whether the official failed to perform his or her duties with the level of diligence required by law and whether this failure resulted in the legally relevant consequences prescribed by the criminal law.

The knowledge of the legal violation is also an important evidentiary criterion. In cases involving intentional abuse, the prosecution must demonstrate that the official was aware of the relevant circumstances and nevertheless acted contrary to the applicable legal requirements. Evidence may include previous administrative decisions, technical reports, official correspondence, written warnings, internal opinions, inspection findings, or electronic records demonstrating that the official had access to information concerning the irregularity.

In negligence cases, the absence of deliberate knowledge or purpose does not necessarily exclude criminal liability. The investigation must instead determine whether the official should and could reasonably have identified the relevant problem while performing his or her duties. This requires an assessment of the official's legal responsibilities, professional competence, access to information, the complexity of the documentation, the foreseeability of the consequences, and the existence of a causal relationship between the failure to exercise due diligence and the resulting damage.

The typical examples also illustrate the distinction. Knowingly issuing a construction permit for an unauthorised or non-compliant project in order to benefit a particular developer may potentially indicate abuse of office. Conversely, issuing a permit without properly examining mandatory documentation, where the official's failure results from inadequate diligence rather than an intention to favour the applicant, may potentially raise the issue of negligence in office.

The evidentiary focus consequently differs between the two forms of liability. In abuse-of-office cases, particular attention must be given to proving intentional conduct and the legally relevant interest or purpose behind the official's actions. In negligence cases, the investigation must concentrate on the scope of the official's duties, the applicable standard of professional diligence, the foreseeability of the harmful consequences, and the causal connection between the omission or improper performance and the resulting damage.

The distinction is therefore not merely theoretical. An incorrect legal classification may have significant consequences for both the individual official and the effectiveness of criminal justice. Treating every unlawful administrative decision as intentional abuse of office could lead to the unjustified criminalisation of administrative errors, professional disagreements, or bona fide decisions made within the scope of legitimate administrative discretion. Conversely, classifying deliberate and motivated misuse of public authority merely as negligence could result in the failure to adequately recognise and prosecute intentional corruption-related or abusive conduct.

This distinction is particularly important in the construction sector because an administrative decision may subsequently be shown to have serious consequences. The annulment of a construction permit, the discovery of an illegal construction, the occurrence of damage to neighbouring property, or the identification of technical deficiencies does not, by itself, establish the mental element of the official

who issued the permit. The criminal investigation must reconstruct the circumstances existing at the time the decision was made and determine what the official knew, what the official was legally required to do, what information was available, and why the official acted or failed to act in a particular manner. The principle of legality and the principle of individualisation of criminal responsibility therefore require a precise assessment of the mental element. The same administrative consequence—such as the issuance of an unlawful construction permit may result from fundamentally different forms of conduct. One official may intentionally disregard the law for the benefit of a private party, while another may make a serious mistake because of inadequate verification, lack of diligence, or failure to properly assess the documentation.

Accordingly, criminal-law analysis should not begin and end with the question of whether the construction permit was lawful. It should additionally determine how and why the unlawful decision was adopted. Only by establishing the subjective attitude of the official, together with the objective elements of the offence, the legally relevant damage, and the causal relationship between the conduct and the consequences, can a correct distinction be made between abuse of office and negligence in office.

This approach ensures an appropriate balance between two competing objectives: effective protection of the public interest against intentional misuse of administrative power and protection of public officials against unjustified criminalisation of bona fide administrative mistakes. Such a balance is particularly important for the Republic of Moldova, where the effectiveness of the construction permitting system depends not only on clear statutory requirements but also on transparent administrative procedures, professional decision-making, institutional supervision, and clearly individualised responsibility.

1.7. THE IMPACT OF ADMINISTRATIVE DECISIONS ON CRIMINAL LIABILITY

An administrative decision may have consequences extending far beyond the immediate applicant.

An unlawfully issued construction permit may enable:

1. construction in violation of an urban development plan;
2. illegal occupation or use of land;
3. infringement of neighbouring property rights;
4. construction in protected areas;
5. environmental damage;
6. deterioration of cultural heritage;
7. creation of risks to public safety;
8. construction of technically unsafe structures; or
9. substantial economic damage to individuals or public authorities.

The Urbanism and Construction Code expressly provides that a permit issued without compliance with urban planning or other statutory requirements may be annulled by the issuer or by a court. It also provides that a person within a local public authority who unlawfully provides the technical or legal basis for issuing a construction permit, or who countersigns or approves the relevant documents, may incur administrative or criminal liability, as appropriate (Parliament of the Republic of Moldova, 2023). This provision creates an important bridge between administrative and criminal law.

The administrative annulment of a permit may constitute significant evidence of unlawfulness, but it should not be treated as automatic proof of a criminal offence. The criminal investigation must independently establish the elements of the relevant offence.

1.6.ADMINISTRATIVED DISCRETION AND LIMITS OF CRIMINALISATION

A particularly difficult issue concerns administrative discretion.

Public officials may have a certain degree of discretion when assessing applications, especially where technical, urban planning or public-interest considerations are involved.

Criminal law should not become an instrument for punishing every administrative decision subsequently considered incorrect.

A distinction must therefore be made between:

a) a legitimate administrative interpretation;
b) an administrative error;
c) an unlawful administrative decision;
d) disciplinary misconduct;

e) administrative or contraventional liability; and
f) criminal conduct.

The existence of disagreement concerning the interpretation of a technical rule does not automatically demonstrate criminal negligence.

Similarly, the subsequent annulment of a construction permit does not by itself prove that the official committed abuse of office.

Criminal law should intervene only where the conduct reaches the threshold established by the Criminal Code.

This approach is especially important because public officials who fear criminal prosecution for every controversial decision may adopt excessively defensive administrative practices, resulting in unnecessary delays and bureaucratisation.

The objective should therefore be accountability without criminalisation of bona fide administrative decision-making.

DISCUSSION AND CONCLUSION

The Moldovan regulatory framework demonstrates a progressive tendency toward individualisation of responsibility in the construction permitting process.

The current Urbanism and Construction Code does not merely establish the applicant's obligations. It also identifies the responsibilities of the issuing authority and the persons who sign construction permits. Article 161 expressly attributes responsibility for the correctness of issued permits to the persons who signed them (Parliament of the Republic of Moldova, 2023).

This approach is important because illegal construction is frequently the result of a chain of decisions rather than a single isolated act.

The applicant may provide incorrect information; the designer may prepare defective documentation; the technical verifier may fail to identify deficiencies; the administrative official may approve the documentation; and another official may sign the final permit.

Consequently, criminal investigation must reconstruct the entire decision-making chain.

The concept of individualised responsibility within a collective administrative process should therefore become a central methodological principle in investigating construction-related offences.

The criminal liability of public officials involved in issuing construction permits represents a particularly important component of the fight against illegal construction and administrative corruption in the Republic of Moldova.

The current Urbanism and Construction Code establishes detailed conditions for issuing construction permits and expressly regulates the responsibilities of issuing authorities and officials. Article 148 imposes specific requirements concerning documentation, verification and compliance with urban planning rules, while Article 161 establishes responsibility for the correctness of permits among the persons who sign them (Parliament of the Republic of Moldova, 2023).

From a criminal-law perspective, the principal distinction must be made between abuse of office under Article 327 and negligence in office under Article 329 of the Criminal Code of the Republic of Moldova (Parliament of the Republic of Moldova, 2002).

Abuse requires intentional unlawful conduct committed for the legally specified interest, whereas negligence concerns failure or improper performance of official duties resulting from a negligent or unconscientious attitude.

The mere unlawfulness or subsequent annulment of a construction permit cannot automatically establish criminal liability. Criminal responsibility requires proof of all elements of the relevant offence, including the mental element, legally significant damage and causation.

For this reason, the investigation of unlawful construction permits should combine legal, administrative, technical, financial and digital evidence.

The study also demonstrates that prevention is as important as repression. Digital permitting systems, transparency, institutional separation of functions, professional training and systematic internal verification can significantly reduce opportunities for abuse and negligence.

Ultimately, the objective of criminal law should not be to punish every administrative error. Its function should be to intervene where an official deliberately transforms public authority into a means of obtaining an unlawful benefit or where a sufficiently serious departure from official duties causes legally relevant harm.

A balanced system of accountability must therefore combine administrative legality, institutional transparency, professional responsibility and proportionate criminal liability. Such an approach is essential for protecting public interests, strengthening confidence in public administration and ensuring lawful and sustainable development of the construction sector in the Republic of Moldova.

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SUBSTANTIVE GENDER EQUALITY THROUGH THE LENS OF FEMINIST LEGAL THEORY: IMPLICATIONS FOR REFORMING VIETNAMESE LAW

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ABSTRACT

Vietnamese law has enshrined the principle of gender equality at both constitutional and statutory levels, yet the gap between normative recognition and women's actual enjoyment of rights remains persistent. This article begins from that paradox to argue that its root cause lies in the continued dominance of a formal equality model, one built on sameness of treatment and gender neutrality, which lacks the capacity to identify or intervene in the power structures, gender stereotypes, and systemic disadvantages that formal neutrality leaves untouched. Employing a method that combines doctrinal analysis with feminist legal theoretical analysis, the article stages a selective dialogue among strands of feminist legal theory, including liberal feminism, Catharine A. MacKinnon's dominance theory, the feminist critique of legal neutrality, Kimberlé Crenshaw's intersectionality, and anti-essentialism, in order to trace the argumentative chain from formal equality to substantive equality and transformative equality. On this basis, the article constructs a four-dimensional analytical framework, comprising disadvantage redress, anti-stereotyping, voice and participation, and structural transformation, that inherits from Sandra Fredman's substantive equality theory while being recalibrated for Vietnam's legal and social context. Applying this framework to the 2013 Constitution, the 2006 Law on Gender Equality, and selected provisions of labour law, the article finds that Vietnamese law has incorporated elements of disadvantage redress and temporary special measures, but still lacks outcome-based impact assessment mechanisms and has not adequately integrated an intersectional perspective on how gender disadvantage interacts with other social axes. The article's contribution is a set of five reform directions that flow directly from the theoretical framework constructed, thereby helping to shift the centre of gravity of Vietnam's gender equality law from formal normative guarantees toward the assurance of equal outcomes and equal capacity to enjoy rights.

Keywords: substantive equality, feminist legal theory, gender equality, intersectionality, structural inequality, Vietnamese law

1. INTRODUCTION

The 2013 Constitution affirms that male and female citizens are equal in all respects and prohibits discrimination on the basis of sex. The 2006 Law on Gender Equality operationalises this principle through provisions on non-discrimination, measures to promote gender equality, and gender mainstreaming in lawmaking. At the level of the written text, it is difficult to argue that Vietnamese law discriminates against women. Yet the gender pay gap in Vietnam still stands at roughly 13.7 per cent of monthly wages, and rises above 50 per cent among certain groups of self-employed workers (International Labour Organization, 2025). Women continue to shoulder the bulk of unpaid care work, remain underrepresented in corporate leadership and elected office relative to men, and the gendered division of labour within household agriculture remains conspicuously patterned (Nguyen, 2022). This is precisely the paradox that demands explanation: law recognises equality, yet inequality persists systematically in the lived enjoyment of rights.

This paradox is not simply evidence of enforcement failure in the narrow sense of inadequate sanctions or insufficient public awareness campaigns. It reflects an internal limitation of the very equality model that the law pursues. When law builds gender equality on a foundation of sameness of treatment and formal neutrality, it tacitly assumes that men and women begin from equivalent social, economic, and institutional conditions, such that removing direct discriminatory treatment suffices to produce equal results. This assumption disregards the fact that women's disadvantage frequently does not stem from any identifiable discriminatory act attributable to a particular actor, but rather from the structural division of labour along gender lines, from stereotypes about caregiving roles, and from legal institutions

built around the typical life experience of men. This is precisely where formal equality, however faithfully enforced, fails to produce substantive equality.

Research on Vietnamese gender equality law to date has largely approached the subject from the standpoint of legal provisions, policy, or sector-specific analysis, such as labour, family, or political participation, with the primary aim of assessing compatibility between domestic law and the CEDAW Convention or proposing textual amendments to statutes (Nguyen, 2022). This approach carries genuine practical value but tends to stop at comparing texts against international standards, without deeply mobilising feminist legal theory as an independent analytical framework capable of reconstructing the legal content of substantive equality itself. This gap is especially conspicuous when set against international scholarship, where the work of Fredman (2016), MacKinnon (1989), and Crenshaw (1989, 1991) has developed incisive analytical tools concerning the relationship between power, gender stereotyping, and law, tools that are rarely applied systematically to Vietnamese law.

Accordingly, the article addresses three research questions. First, how does substantive gender equality differ from formal equality, and why does this shift matter for gender equality law? Second, how do the various schools and methods of feminist legal theory explain why gender-neutral law can nonetheless generate or sustain actual gender inequality? Third, drawing on the substantive equality approach within feminist legal theory, along which principles and mechanisms should Vietnamese law be recalibrated to move from guaranteeing equality on paper toward guaranteeing equality in outcomes and in the capacity to enjoy rights?

Methodologically, the article combines legal-theoretical analysis with doctrinal and selective comparative analysis. The theoretical section is built through scholarly dialogue, situating strands of feminist legal theory in argumentative relation to one another and to substantive equality theory, rather than through sequential summary. The assessment of Vietnamese law draws on doctrinal analysis anchored in empirical data from reports by the International Labour Organization and the World Bank, while carefully distinguishing correlation, structural disadvantage, and discrimination so as to avoid overreaching inferences.

The article's contribution operates on two levels. Theoretically, it constructs a four-dimensional framework for analysing substantive gender equality, disadvantage redress, anti-stereotyping, voice and participation, and structural transformation, built through a critical synthesis of Fredman's substantive equality theory and strands of feminist legal theory, while recalibrating this framework for the institutional and legal-cultural specificities of Vietnam. Practically, the article deploys this same four-dimensional framework to evaluate Vietnamese law and to propose reform directions grounded directly in theory, rather than offering generic policy recommendations detached from theoretical foundations.

2. FROM FORMAL TO SUBSTANTIVE EQUALITY: A SHIFT IN LEGAL THINKING ABOUT GENDER

2.1. Formal equality and the limits of the sameness principle

The principle of formal equality, or equality as sameness, requires that persons in like positions be treated alike, and prohibits less favourable treatment on the basis of a protected characteristic such as sex. This principle underlies equal treatment doctrine and what American constitutional law terms the anti-classification principle. Historically, this principle achieved much in dismantling overt legal barriers that excluded women from suffrage, property ownership, and labour market participation (Fredman & Goldblatt, 2015). The value of this achievement cannot be denied. But precisely because formal equality operates through comparison with a similarly situated person, it reveals structural limitations whenever women's disadvantage does not originate in a specific discriminatory act but in the entire social foundation upon which the legal norm itself was constructed.

The crux of this critique lies in the concept of the hidden male norm underlying institutions that appear neutral. Fredman and Goldblatt (2015) recall MacKinnon's well-known observation that under the sameness standard, women are measured by their degree of correspondence to men, such that gender neutrality in practice is simply the male standard clothed in universal form. This is not a rhetorical overstatement but points to a concrete operative mechanism of law: when a norm governing recruitment, promotion, or performance evaluation is built around the model of a worker unencumbered by responsibility for childcare or family obligations, a model historically associated with men, that norm remains applied "the same way" to both sexes while placing women, who continue to shoulder the bulk of unpaid care work, in a systematically disadvantaged position.

Two strands of scholarly opinion should be distinguished here to avoid oversimplification. One strand, associated with traditional liberal feminism, treats formal equality as a necessary and, in the long run, sufficient condition, on the premise that once overt legal barriers are removed, markets and society will self-correct toward fairness so long as individual merit is assessed objectively. This strand has been instrumental in advancing foundational legal reforms but has been sharply criticised for assuming that the "objectivity" of merit standards is itself neutral, when in fact such standards have been shaped by the typical lived experience of men (Fredman, 2016). A second strand, developed from dominance theory and substantive equality theory, holds that so long as social institutions, from working-hour structures to promotion criteria to definitions of professional competence, remain built upon a pre-existing gendered division of labour, formal equality will merely reproduce inequality under a textually neutral guise.

The present author's own assessment is that both strands rest on legitimate empirical grounds, but the fundamental difference lies in their unit of analysis. Liberal feminism analyses at the individual level and treats direct legal barriers as the object to be eliminated. Substantive equality theory and dominance theory analyse at the structural level and treat the seemingly neutral standards themselves as objects requiring interrogation. In Vietnam, where direct legal barriers were largely dismantled in the years following the enactment of the 2006 Law on Gender Equality, the more practically significant question is no longer whether the law discriminates overtly, but whether seemingly neutral standards in recruitment, promotion, and household resource allocation are quietly reproducing disadvantage for women. This is precisely why the following section turns to the substantive equality model.

2.2. Substantive equality as a disadvantage-redressing model

Where formal equality asks whether two people are treated alike, substantive equality asks an altogether different question: whether a person genuinely has the capacity to enjoy rights equally in practice, regardless of whether the norm applied to them is textually neutral. Fredman (2016) argues that substantive equality should not be reduced to any single formula such as equality of opportunity or equality of outcome, since each formula carries distinct strengths and weaknesses. Equality of opportunity extends the scope of equality beyond formal treatment, but still assumes that if opportunities are opened fairly, differential outcomes are justified, an assumption that ignores how historical disadvantage may leave different groups unable to seize opportunities in the same way. Equality of outcome, conversely, centres directly on final results but is vulnerable to criticism for potentially requiring deep intrusion into individual choice.

Building on a critique of both single formulas, Fredman (2016) proposes a composite model comprising four elements: redressing disadvantage, that is, levelling up the position of the disadvantaged group rather than levelling down the advantaged group's standard; countering prejudice, stereotyping, stigma, and violence linked to the protected characteristic; accommodating difference and transforming the institutional and social structures that sustain disadvantage, rather than compelling the disadvantaged group to conform to a pre-established standard; and enhancing the voice and political and social participation of the disadvantaged group. This four-dimensional approach carries the important merit of refusing to rank one dimension above the others, requiring instead that they interact with and calibrate one another, since, for example, a redistributive measure may itself generate stigmatic harm if poorly designed, as when welfare benefits inadvertently label recipients as "lacking capacity" (Fredman & Goldblatt, 2015).

Three concepts frequently conflated deserve careful distinction: equality of treatment requires sameness of formal treatment; equality of opportunity requires the removal of access barriers without guaranteeing outcomes; equality of outcome is concerned directly with the distribution of final results. Substantive equality as Fredman conceives it is not coextensive with any single one of these three concepts, but selectively integrates elements of all three while adding a positive obligation on the State, that is, a responsibility not merely to refrain from discrimination but actively to design policy and law to redress structural disadvantage. This positive obligation finds reinforcement in international human rights law through CEDAW General Recommendation No. 25, which establishes that temporary special measures aimed at accelerating de facto equality are not to be considered discrimination, and through General Recommendation No. 28, which establishes that States parties bear obligations not only to respect but also to protect and fulfil women's right to non-discrimination (CEDAW Committee, 2004, 2010).

A further point worth noting, and one that supplements the analysis of State responsibility, concerns Fineman's vulnerability theory approach. Fineman (2008) critiques the autonomous, self-sufficient legal subject that underlies classical legal theory, arguing that vulnerability is universal and inherent to the human condition rather than a characteristic peculiar to any particular social group. From this, Fineman contends that the State bears responsibility for restructuring social institutions to accommodate the care and interdependence inherent in human life, rather than treating dependency as an exception to be "handled" separately for groups deemed weak (Fineman, 2019). Applied to gender equality analysis, this approach supplies an important additional reason why caregiving responsibility within the family, currently distributed asymmetrically to women, should not be regarded as a neutral individual choice but as the outcome of a social structure that fails adequately to recognise the State's responsibility to support care work.

2.3. From substantive equality to transformative equality

Substantive equality, though it surpasses the limits of formal equality, can still be implemented in a manner that merely compensates individual disadvantage without disturbing the structures that produce it. A financial support programme for poor women upon childbirth, for instance, may redress an immediate portion of disadvantage, but absent an accompanying shift in how caregiving responsibility is allocated between men and women, that programme leaves untouched the gendered division of labour that generated the disadvantage in the first place.

This marks the distinction between substantive equality in the narrow sense, focused on compensating and adjusting outcomes for disadvantaged individuals or groups, and transformative equality, which demands that law intervene in the very institutional structures and social relations that produced the disadvantage. Fredman (2016) treats the "accommodating difference and transforming structures" dimension as one of the four dimensions of substantive equality, yet emphasises that this dimension is more ambitious than the other three, since it requires not merely that the State compensate but that it change the very institutions, from working hours to competence criteria to the organisation of public and private space, that anchor women's disadvantaged position.

It is precisely here that substantive equality theory alone cannot fully explain why such structures were formed and continue to be sustained. This is the gap that feminist legal theory, particularly its analyses of power and domination, is positioned to fill. If substantive equality theory supplies the evaluative criteria and the goal to be achieved, feminist legal theory supplies the analytical tools for understanding why structures of inequality are so persistently reproduced even where law has declared itself gender neutral. The following section develops those analytical tools.

3. RECONCEIVING SUBSTANTIVE EQUALITY THROUGH FEMINIST LEGAL THEORY

3.1. Critiquing the neutrality of law

The foundational assumption of modern law is that law is objective, universal, and neutral, applying identically to every subject regardless of personal characteristics. Feminist legal theory does not deny that law can be applied with formal consistency, but poses a deeper question: whether the very content of legal standards, not merely how they are applied, reflects the social experience of one sex more than the other.

Carol Smart (1989) develops this critique by analysing law's power as a discourse, arguing that law does not merely overlook women's experience but actively disqualifies the validity of that experience and knowledge, while asserting its own authority to render social issues correct in its own language and categories. On Smart's account, when feminist movements bring social problems, such as domestic violence or workplace discrimination, within the ambit of legal regulation, the very process of "translating" these problems into legal language can strip them of their original social meaning, rendering law simultaneously a tool and an obstacle for feminist objectives.

In a different but complementary direction, Katharine Bartlett (1990) develops specific feminist legal methods, most notably the technique of "asking the woman question", which examines whether a legal rule, however neutrally worded, overlooks or disadvantages women, and the technique of feminist practical reasoning, which resolves concrete legal situations by reference to actual context rather than by applying pre-established abstract categories. Bartlett does not deny the value of systematicity in law, but argues that traditional legal reasoning, built on categories established in advance, tends to obscure

precisely those experiences that do not fit those categories, and women's experience frequently constitutes exactly that kind of obscured experience.

Comparing these two approaches reveals an important distinction relevant to concrete legal analysis. Smart's approach is more thoroughly sceptical about law's capacity for reform, closer to the post-structuralist tradition, whereas Bartlett's approach retains confidence in the possibility of improving law from within through alternative methods of reasoning. This article leans toward Bartlett's more pragmatic approach, since its research aim is to propose concrete legal reform, while nonetheless absorbing Smart's warning that any effort to reform gender equality law must remain self-reflexive about the risk that legal discourse itself may diminish or distort the original goal of justice, as when protective labour measures for women are converted into grounds for employers to discriminate against them in reverse.

The central question this section poses, whether a legal standard applied identically to everyone is genuinely equal if that standard was constructed on the predominant social experience of men, must be answered conditionally. The answer is no, if the standard was built without regard to differences in the division of labour, caregiving responsibility, or experiences of harm between the sexes, and where applying it "identically" has the effect of sustaining rather than reducing existing disadvantage. Conversely, a formally neutral standard can remain compatible with substantive equality if it was designed after accounting for and adjusting to differences in starting conditions. This suggests that the issue is not whether law is "neutral" as such, but whether the lawmaking process genuinely identified structural disadvantage before designing the norm.

3.2. Power, domination, and structural gender inequality

Among the strands of feminist legal theory, Catharine A. MacKinnon's dominance theory offers the most radical analysis of the relationship between power and law. MacKinnon's (1989) starting point is a rejection of the "sameness versus difference" framework for analysing gender equality, arguing that both poles of this axis misconceive the problem. If law requires women to resemble men in order to claim equal rights, it forces women to renounce or conceal differences bound up with their social position. If law recognises women's difference to justify differential treatment, it risks reaffirming precisely the stereotypes historically used to subordinate women. MacKinnon (1987) proposes replacing the "sameness versus difference" axis with a "dominance versus subordination" axis, arguing that the core problem of gender inequality is not an irrational classification between two groups with differing characteristics, but a power relation in which one group imposes domination upon another, with sex and sexuality constituting one of the principal axes organising that relation of domination in society.

Caution is warranted in presenting dominance theory so as to avoid oversimplification. MacKinnon does not argue that every gender difference is merely a manifestation of one-directional power imposition, but rather that the social meaning of gender difference, that is, how society assigns value and position to such differences, is constructed within a system of asymmetrical power relations between the sexes. On this reading, the legally significant question is not "in what respects do men and women differ" but "how is difference interpreted and encoded by institutions built by the group that holds dominant power". This is why MacKinnon so forcefully criticises equality principles grounded in comparison with a similarly situated person, since such principles assume legal categories are neutral, when in fact the very determination of who counts as "similarly situated" already reflects the standpoint of the group holding power to shape the law.

A significant rebuttal to dominance theory, particularly from anti-essentialist scholars, holds that MacKinnon's portrayal of women as a homogeneous dominated group risks overlooking the enormous differences in the experience of domination among different groups of women, for instance between middle-class white women and working-class women of colour in the United States. This is a well-founded rebuttal that will be examined more closely in section 3.3. Nonetheless, this article's own assessment is that this rebuttal does not diminish the analytical value at the core of dominance theory, namely its treatment of gender inequality as a problem of power structure rather than merely a problem of classification or differential treatment. What requires adjustment is scope of application: rather than treating "women" as a homogeneous block subject to a single uniform mode of domination, one must recognise that power relations between the sexes always intersect with other axes of power, a point that MacKinnon's own analytical axis, if extended, is entirely capable of accommodating.

Applied to this article's research aim, dominance theory's most important contribution to substantive equality theory is that it compels one to ask about the power structure lying behind disadvantage, rather than resting content with describing disadvantage as a fact requiring compensation. Applying Fredman's four dimensions alone, without asking why the gendered division of labour or stereotypes about caregiving roles are so persistently sustained, risks producing compensatory measures that treat symptoms while leaving the source untouched. Dominance theory reminds us that this source lies in institutionalised power relations, including within legal institutions that present themselves as neutral, and that substantive equality, if it is to be genuinely "substantive", must interrogate this power relation rather than merely adjust distributive outcomes.

3.3. Intersectionality and the limits of the homogeneous subject "woman"

Crenshaw (1989) develops the concept of intersectionality from analysing discrimination litigation in the United States, in which Black women could not establish discrimination claims because the anti-discrimination legal system permitted claims on only a single ground, race or sex, without recognising that their disadvantage arose from the simultaneous intersection of both grounds. If a firm hires Black men into manual labour positions and white women into clerical positions, but hires no Black women into any position, analysis based on race alone or sex alone would fail to detect that injustice, since on each axis taken separately the firm can point to hiring both people of colour and women. Building on this analysis, Crenshaw (1991) extends the concept of intersectionality to violence against women of colour, showing that public policy and social movements are often designed around the typical experience of the majority group within each category, leaving women positioned at the intersection of multiple disadvantages doubly marginalised, both within anti-racist policy premised on Black men's experience and within feminist movements premised on white women's experience.

Anti-essentialism, developed into a systematic critique by Angela Harris (1990), goes a step further by criticising the very way certain feminist scholars, MacKinnon included, construct theory upon an assumed unified "women's experience" separable from race, class, and other factors. Harris (1990) argues that when feminist theory takes the experience of middle-class white women as its implicit reference point, the experience of women of colour is admitted only as an "additive" variant of the standard experience, rather than being recognised as a socially structured position in its own right. This is why Harris proposes the concept of "multiple consciousness", holding that the identity of an individual, particularly a doubly marginalised woman, is constituted from multiple, sometimes inconsistent and contradictory, fragments of experience, rather than from a single unified essence.

An important point in applying intersectionality to the Vietnamese context is to avoid mechanically imposing social categories peculiar to the United States, particularly the category of race in its American historical sense, onto a society with a distinct structure of stratification. In Vietnam, the axes of intersection with greater practical bearing on gender disadvantage include geographic region, particularly the divide between urban centres and rural or mountainous areas, ethnic minority status, domestic labour migration, formal versus informal employment, and multigenerational caregiving responsibility. Data from the International Labour Organization show that the gender pay gap in Vietnam is not uniform across regions and sectors: the average monthly wage gap stands at roughly 13.7 per cent, yet reaches 28.4 per cent among skilled agricultural, forestry, and fishery workers as of 2019, and exceeds 50 per cent among certain groups of self-employed workers (International Labour Organization, 2025). This stratification demonstrates that gender disadvantage in Vietnam intersects strongly with economic sector and place of residence, and that a gender equality policy uniformly designed for "Vietnamese women" in general risks overlooking precisely the groups of women bearing the heaviest disadvantage.

This article's own assessment is that adapting intersectionality to the Vietnamese context does not mean abandoning Crenshaw's original framework, but rather substituting the specific content of the intersecting axes to fit Vietnam's social structure, while preserving the core analytical logic: gender disadvantage is not evenly distributed among women, and a policy neutral with respect to gender at the aggregate level can still obscure unjust distribution at the level of narrower subgroups. The important practical application of this logic, elaborated in Part 5, is a requirement that gender impact assessment in lawmaking be designed to detect differential impacts among different groups of women, not merely between men and women in general.

3.4. From substantive equality to social structural transformation

Synthesising the analyses of the three preceding sections yields an understanding of substantive gender equality that functions as a more concrete analytical tool for law than the mere application of Fredman's original four-dimensional framework. The critique of legal neutrality, following Smart and Bartlett, shows the need to reconsider the very content and method of legal reasoning, not merely outcomes of application. MacKinnon's dominance theory shows the need to interrogate the power structure lying behind stereotypes and disadvantage, not merely the distribution of outcomes. Crenshaw's intersectionality and Harris's anti-essentialism show the need to refuse treating "women" as a homogeneous legal subject and to account for the intersection between gender and other social factors.
On this basis, the article proposes a four-dimensional framework for analysing substantive gender equality, inheriting directly from Fredman's (2016) four-dimensional framework but reinterpreted and supplemented with analytical tools from feminist legal theory:

- **The first dimension, redressing disadvantage**, retains substantive equality theory intact, but adds the requirement that identifying disadvantage must rest on power-structural analysis drawn from dominance theory, not merely on statistical analysis of outcome gaps.
- **The second dimension, countering prejudice, stereotyping, and stigma**, is supplemented with analytical tools from the critique of legal neutrality, such that identifying gender stereotyping must extend to stereotypes concealed within seemingly neutral legal standards, not only overt and direct prejudice.
- **The third dimension, enhancing voice and participation**, is supplemented with a requirement of diverse representation drawn from intersectionality, such that ensuring "women's" voice in policymaking must ensure the voices of women's groups differentiated by region, ethnicity, and employment status, not only the voice of women's groups in more socially advantaged positions.
- **The fourth dimension, transforming the structures and power relations that generate inequality**, is the most ambitious dimension and directly embodies dominance theory's contribution, requiring that law intervene not merely in distributive outcomes but in the very institutions, caregiving labour division, working-hour structures, professional competence criteria, that reproduce asymmetric power relations between the sexes.

It bears emphasis that this four-dimensional framework is not a mechanical assemblage of theoretical strands, but a critical synthesis in which each strand supplies analytical tools for specific dimensions of substantive equality theory. This constitutes the article's central theoretical contribution, and this framework will be applied consistently in Part 4 to evaluate Vietnamese law and in Part 5 to construct legal reform proposals.

4. EVALUATING VIETNAMESE LAW THROUGH THE LENS OF SUBSTANTIVE EQUALITY

4.1. Elements of substantive equality already recognised in Vietnamese law

Assessed against the four-dimensional framework constructed in section 3.4, Vietnamese law has recognised several important elements of substantive equality, particularly within the disadvantage-redress dimension. Article 4 of the 2006 Law on Gender Equality identifies the objective of gender equality as eliminating gender discrimination, creating equal opportunity for men and women in socio-economic development and human resource development, moving toward substantive gender equality between men and women, demonstrating that the statute has proactively adopted the terminology of "substantive equality" rather than stopping at formal equality (Nguyen, 2022). Article 19 of this law sets out measures to promote gender equality in the labour field, including quotas for recruitment by sex, capacity-building training for women workers, and safe working conditions for women employed in certain arduous or hazardous occupations. These provisions clearly embody the disadvantage-redress dimension in the sense that they are non-neutral measures, designed specifically for one sex in order to compensate an existing disadvantaged position, consistent with the logic of temporary special measures under Article 4(1) of CEDAW (CEDAW Committee, 2004).
Within the voice-and-participation dimension, Vietnamese law also contains provisions on the proportion of women serving in elected bodies and in cadre planning, reflecting recognition that women's political representation cannot be achieved merely by guaranteeing formally equal eligibility to stand for election. The mainstreaming of gender equality concerns in the drafting of normative legal documents, mandated under the 2015 Law on Promulgation of Legal Normative Documents, likewise

represents a meaningful advance, since it introduces a requirement for gender impact assessment at the drafting stage itself, rather than addressing discrimination only after it has occurred.

An objective assessment suggests these advances should not be undervalued. Relative to many countries in the region, Vietnamese law's recognition of the concept of substantive equality and its design of a mechanism for measures promoting gender equality directly within sectoral legislation constitutes a meaningful step, laying a legal foundation for disadvantage-redressing interventions that many other legal systems achieve only gradually through case law or legal doctrine over time.

4.2. Traces of formal equality thinking in current law

However, when examined against the second and fourth dimensions of the analytical framework, countering stereotyping and transforming power structures, Vietnamese law still bears deep traces of formal equality thinking. The prevailing structure of gender equality provisions, including within the Law on Gender Equality itself, still follows a model of prohibiting direct discriminatory conduct, that is, identifying specific prohibited acts such as discrimination in recruitment, pay, or appointment based on sex, without yet building an effective mechanism to address indirect disadvantage, that is, provisions or practices that appear neutral but produce disproportionately adverse effects on one sex.

A telling example lies in provisions protecting women workers in certain arduous or hazardous occupations. Though motivated by a genuine intent to protect women workers' reproductive health, the design of these provisions, if confined to restricting the scope of work women are permitted to perform without an accompanying mechanism to expand equivalent career opportunities, risks reproducing stereotypes about women workers' "fragility", a dynamic that Vietnamese socio-legal research has documented in analysing analogous support provisions under the Law on Gender Equality (Nguyen, 2022). Nguyen (2022) specifically analyses how support provisions concerning training and protective working conditions for women, despite positive intent, may inadvertently mark women as a group "requiring protection" or "less capable", thereby heightening employer bias when considering the recruitment of women workers, particularly out of concern over maternity leave.

This is precisely the phenomenon that Fredman (2016) warns against regarding the interaction among the dimensions of substantive equality: a redistributive measure aimed at redressing disadvantage (dimension one) can generate stigmatic harm (dimension two) if not carefully designed, and absent accompanying broader structural change (dimension four), such a measure risks becoming a mechanism that sustains rather than dismantles gender stereotyping. Notably, Vietnamese law, in designing measures to promote gender equality, appears to concentrate chiefly on dimension one without a mechanism to review the effects of such measures on dimension two, that is, lacking a step to assess whether a protective measure is inadvertently reinforcing stereotypes about women's weakness.

Regarding the structural transformation dimension, Vietnamese labour law and family law fundamentally continue to treat the allocation of family caregiving responsibility as a private matter, falling within the scope of voluntary agreement among family members, without a legal mechanism actively encouraging or requiring a more balanced sharing of caregiving responsibility between men and women, for instance through a period of care leave reserved for and non-transferable from fathers. This gap conspicuously reflects the traditional public-private boundary in law, which Charlesworth, Chinkin, and Wright (1991) criticised in the context of international law by showing that treating the family sphere as "private" and beyond the scope of active State regulation is precisely one of the most significant mechanisms by which gender inequality within the family is sustained despite equality commitments in the public sphere.

4.3. The gap between legal neutrality and actual inequality

Empirical data on Vietnam's labour market allow for a concrete illustration of the gap between legal neutrality and actual inequality, while demanding care in distinguishing statistical correlation, structural disadvantage, and discrimination. According to International Labour Organization reporting, the monthly gender wage gap in Vietnam stood at roughly 13.7 per cent in 2019, and this gap is not uniform across sectors, ranging from relatively low levels in certain industries to over 50 per cent among certain groups of self-employed workers (International Labour Organization, 2025). World Bank reporting likewise shows that working women in Vietnam tend to concentrate in lower-paying occupations relative to men with equivalent educational attainment, place of residence, and age (World Bank, 2019). One should not infer simplistically that this entire gap constitutes direct evidence of discrimination in the legal sense, that is, less favourable treatment attributable to a specific actor. Part of the gap reflects

the differing distribution of occupation and qualification between the sexes, a phenomenon commonly termed occupational segregation, which itself is the consequence of accumulated socialisation processes and gender stereotyping over many years, not the outcome of a single discriminatory decision. This is precisely the boundary requiring careful distinction: statistical correlation between sex and wage level does not by itself establish discrimination, but it is a strong indicator of structural disadvantage, that is, a condition in which the structure of the division of labour, stereotypes about "occupations suitable for women", and the burden of unpaid care work have already shaped women's career trajectories toward disadvantage before they even enter the labour market.

It is precisely the gap between correlation, structural disadvantage arising from accumulated social factors, and discrimination, attributable discriminatory conduct, that formal-equality-model anti-discrimination law lacks the tools to address. Direct anti-discrimination law can address only the third scenario, where it can be shown that a specific actor treated an individual less favourably because of their sex. It has no tool to address the second scenario, where disadvantage arises from the entire social structure without any identifiable "violating actor". This is precisely why research on the gender pay gap in Vietnam typically concludes that measures extending beyond the traditional anti-discrimination framework are required, such as investment in public childcare services, improving working conditions in sectors where women predominate, and promoting men's participation in family care work (International Labour Organization, 2024, 2025).

5. IMPLICATIONS FOR REFORMING VIETNAMESE LAW

5.1. Reconceiving the legal content of gender equality toward substantive equality

The current problem is that the concept of gender equality in Article 5 of the 2006 Law on Gender Equality, though referencing "substantive equality" as an objective, still defines gender equality chiefly through the lens of non-discrimination and equal opportunity, without clearly linking that definition to the requirement of capacity to enjoy rights and to actual outcomes. The feminist theoretical basis explaining this problem lies in the fact that when the legal definition of gender equality does not explicitly require the redress of structural disadvantage, enforcing bodies, including courts and administrative agencies, tend by default to apply the sameness-of-treatment standard when resolving concrete disputes, since this standard is easier to apply and less contentious than a standard requiring assessment of structural impact, precisely as MacKinnon (1987) critiques the sameness standard for becoming the "default standard" whenever law fails to explicitly require otherwise.

Vietnamese law should be revised to make explicit, within the statutory text itself, that gender equality is not synonymous with identical treatment, and that differential treatment aimed at redressing structural disadvantage or responding to the specific needs of one sex does not constitute discrimination, provided such measures aim to promote substantive equality and are designed not to persist indefinitely. This aligns with the logic of Article 4(1) of CEDAW and General Recommendation No. 25 (CEDAW Committee, 2004), but more importantly, this recommendation flows directly from the four-dimensional framework constructed in section 3.4: if gender equality is defined in connection with the four dimensions of redressing disadvantage, countering stereotyping, enhancing participation, and transforming structures, then applying a standard of differential treatment for redressive purposes acquires a far clearer legal foundation than under current conditions.

5.2. Shifting the focus from prohibiting discrimination to redressing structural disadvantage

The current problem, as analysed in section 4.2, is that Vietnamese gender equality law remains concentrated chiefly on a model prohibiting direct discriminatory conduct, while lacking a mechanism to address indirect disadvantage or structural disadvantage unconnected to any specific violating act. The feminist theoretical basis explaining this problem is precisely dominance theory's and substantive equality theory's analysis of the limits of the sameness principle when applied to systemic disadvantage lacking an identifiable "violating actor" (MacKinnon, 1989; Fredman, 2016).

Vietnamese law should be strengthened to develop the State's positive obligations, along lines similar to the CEDAW Committee's guidance on the obligations to respect, protect, and fulfil (CEDAW Committee, 2010). Specifically, a legal mechanism is needed requiring State agencies, and, to an appropriate extent, private-sector employers, to proactively review and adjust policies or practices that appear neutral but produce disproportionately adverse effects on one sex, even absent discriminatory intent. This is precisely the logic of indirect discrimination or disparate impact, a concept many legal

systems have developed to remedy the limitations of the sameness principle (Fredman & Goldblatt, 2015). Introducing this concept into Vietnamese law, accompanied by a concrete impact assessment mechanism, would constitute an important shift in focus from a model addressing only individual violations toward one actively redressing structural disadvantage.

5.3. Strengthening the mechanism for measures promoting gender equality

The current problem, as analysed in section 4.2, is that measures promoting gender equality under current Vietnamese law, though legally grounded, have not been designed with an accompanying mechanism to assess secondary effects on stereotyping and stigma, risking that certain protective measures for women workers inadvertently reinforce bias about women's capability. The feminist theoretical basis explaining this problem lies in the interaction among the dimensions of substantive equality under Fredman (2016) and in anti-essentialism's critique of the risk that "protective" measures for women reaffirm stereotypes of weakness (Harris, 1990).

Here it is necessary to confront directly the frequently raised objection that granting preferential measures to women conflicts with the principle of equality, since it creates differential treatment based on sex. This objection stems from an understanding of equality premised on identical treatment, treating any differential treatment as a violation of the equality principle regardless of its purpose. The theoretical basis for rejecting this objection lies precisely in the asymmetry characteristic of substantive equality that Fredman (2016) and Fredman and Goldblatt (2015) analyse: the substantive equality principle distinguishes between differential treatment that sustains or aggravates existing disadvantage, which is prohibited, and differential treatment that redresses existing disadvantage, which is permitted and indeed required. Temporary special measures under Article 4(1) of CEDAW do not "break" the equality principle but implement that very principle at a deeper level, since the ultimate goal remains equality in fact, differing only in recognising that achieving that goal requires different pathways from different starting positions (CEDAW Committee, 2004).

An important condition for preferential measures to avoid the risk that anti-essentialism warns against is that such measures must be genuinely temporary, that is, designed with specific objectives and termination criteria once de facto equality has been achieved, and must be periodically evaluated for secondary effects on gender stereotyping. Vietnamese law should add such a periodic evaluation mechanism for existing measures promoting gender equality, particularly in the labour field, to determine which measures are genuinely advancing disadvantage redress and which risk reinforcing stereotypes of women's weakness and therefore require redesign toward expanding opportunity rather than restricting the scope of permissible work.

5.4. Integrating intersectionality into gender impact assessment in lawmaking

The current problem is that the gender mainstreaming mechanism in drafting normative legal documents in Vietnam, though mandated under the Law on Promulgation of Legal Normative Documents, is typically implemented through a model assessing differential impact between men and women in general, without a requirement to assess differential impact among different groups of women. The feminist theoretical basis explaining this problem is precisely Crenshaw's (1989, 1991) intersectionality, which shows that a policy with an average positive impact on "women in general" can still overlook or disadvantage groups of women positioned at the intersection of multiple disadvantages.

Applied to the Vietnamese context, as analysed in section 3.3, the axes of intersection carrying significant practical weight include urban versus rural or mountainous residence, ethnic minority status, formal versus informal employment, and labour migration status. Vietnamese law should add a specific requirement within the gender impact assessment process, obliging drafting agencies to disaggregate data and assess impact along at least these intersecting axes, not merely along the single axis of sex. For instance, a childbirth financial support policy should be assessed separately for its impact on ethnic minority women in mountainous areas compared with women in urban areas, since the needs and access barriers of these two groups may differ substantially, consistent with what Charlesworth (1999) terms "looking for silences", that is, actively seeking out experiences overlooked by policy analysis conducted at the aggregate level.

5.5. Building an outcome-based equality assessment mechanism

The current problem is that Vietnam's mechanism for monitoring the implementation of gender equality law is concentrated chiefly on verifying textual compatibility between domestic legislation and equality

standards, while lacking a systematic mechanism to assess the actual impact of law on the gender gap on the ground. The feminist theoretical basis explaining this problem lies in the article's entire central argument: if formal equality can coexist with substantive inequality, then merely checking the neutrality of legal text is insufficient to detect or remedy existing inequality.

Vietnamese law should add an outcome-based assessment mechanism, using quantitative indicators such as the gender pay gap disaggregated by sector and region, the proportion of women in leadership positions, and the distribution of unpaid care work, similar to the approach taken in reports by the International Labour Organization and the World Bank (International Labour Organization, 2024, 2025; World Bank, 2019). The critical point is that this mechanism must be institutionalised as a mandatory component of periodic law review and amendment processes, not merely as independent research conducted by international organisations. At the same time, as noted in section 4.3, this assessment mechanism must be carefully designed to distinguish statistical correlation, structural disadvantage, and discrimination, avoiding the inference that every outcome gap demands the same type of legal intervention, and instead identifying which gaps stem from remaining legal barriers, which stem from social stereotyping requiring education and communication tools, and which stem from deficits in public services, such as childcare, requiring public investment.

6. CONCLUSION

This article began from the paradox between the recognition of gender equality at the normative level and the persistent existence of gender inequality in the lived enjoyment of rights in Vietnam, arguing that the root of this paradox lies in the structural limitations of the formal equality model. Through selective dialogue among strands of feminist legal theory, the article has traced the argumentative chain from formal equality, through the limits of the sameness model, to structural inequality, substantive equality, and the transformative potential of law. The article's central theoretical finding is that substantive equality, when illuminated by feminist legal theory, requires not merely that law eliminate specific discriminatory acts, but that law possess the capacity to identify and progressively transform the power structures, gender stereotypes, and socio-economic conditions that render women unable to enjoy rights equally in practice, regardless of whether the norm applied to them is textually neutral.

The research's contribution to the theory of gender equality law in Vietnam lies in constructing and applying a four-dimensional analytical framework, redressing disadvantage, countering stereotyping, ensuring voice and participation, and transforming power structures, developed through a critical synthesis of Fredman's substantive equality theory and the analytical tools of dominance theory, the critique of legal neutrality, and intersectionality, while adapting this framework to the specific features of Vietnam's social structure. Unlike prior research that has predominantly analysed gender equality from a normative standpoint or through technical comparison with CEDAW, this article has used this very theoretical framework as a diagnostic tool to identify where Vietnamese law still bears the imprint of formal equality thinking despite employing the language of substantive equality, and has derived reform directions directly from that theoretical foundation. Future research might extend this analytical framework to other specific fields of law, such as family law or the law governing technology and artificial intelligence in the context of differential gender impact, or undertake empirical research to test the extent to which Vietnamese enforcement bodies have absorbed a substantive understanding of equality in actual practice.

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SHARED COGNITIVE INFLUENCE AND UNSANCTIONED TRIAL: IMPLICATIONS FOR HUMAN RIGHTS, CORPORATE REPUTATION AND ECONOMIC GOVERNANCE

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Abstract
The way society views, assesses, and reacts to accusations of misconduct has changed as a result of the quick development of digital communication and networked information environments. The public's perceptions of guilt, innocence, credibility, and culpability are shaped by narratives disseminated through media and digital platforms prior to the conclusion of a legally sanctioned legal process. In this context, collective cognitive influence can increasingly function as a form of informal adjudicatory power. Due process, the presumption of innocence, privacy, dignity, and other essential human rights are all seriously threatened by this phenomenon, which is conceptualized in this work as "Shared Cognitive Influence and Unsanctioned Trial."
Particularly in cases involving individuals and corporate entities, the study critically investigates how the creation of premature public judgments may serve as a type of extrajudicial adjudication. Even in the absence of a court ruling, unchecked cognitive influence has the potential to turn public opinion into a punitive mechanism capable of causing social exclusion, reputational harm, and irreversible consequences. However, public discourse is an essential part of democratic accountability. Such reputational shocks may have an impact on stakeholder relations, investor confidence, market valuation, and overall economic stability in a business setting.
Adopting a socio-legal and interdisciplinary approach, the study analyses the tension between freedom of expression, public accountability, fair trial guarantees, and reputational interests. It seeks to examine the legal and regulatory mechanisms necessary to balance public participation with procedural fairness and to develop a rights-sensitive framework for addressing unsanctioned public trials in contemporary information societies. The study ultimately argues for a calibrated approach that preserves democratic discourse while preventing public perception from substituting legally established adjudication.
Keywords: Shared Cognitive Influence, Extra-Judicial Adjudication, Public Opinion, Presumption of Innocence, Due Process, Corporate Reputation**.**

1. INTRODUCTION

One of the very essential foundations of democracy and markets is a common cognitive environment, shared assumptions, beliefs and expectations among citizens, consumers and investors. Now two processes threaten that environment. The first is shared cognitive shaping the indirect, intentional manipulation, at mass scale, of collective beliefs, unconsented, via social media influence operations, computational propaganda, algorithmic amplification, psychographic microtargeting and AI-generated content. The second is the unapproved trial: a goal (electoral, commercial, technological or geopolitical) for which the means have not been debated or subject to public feedback or regulation or, in short, to real informed consent (Rehman, Ikhlaq ur 2019). The most recent example of both is the Cambridge Analytica scandal of 2018, where behavioural data from more than 100 million users was harvested without their consent and used to create personalised psychological campaigns and "behind voters' backs". They are important to three groups at the same time and for this reason, they do not lend themselves to single discipline analysis, Human rights systems in which influence operations are used to restrict rights and to manipulate the facts in which rights are enjoyed. Corporate governance, companies are at the same time the source, object and victim of manipulation; there are measurable repercussions to their reputation and finances (Bakir, V. 2020). Economic governance, in which misinformation redefines the flow of information in the market, has a knock-on effect and leads to

regulatory action which, in turn, influences company behaviour. Both phenomena have changed in structure since the digital substrate; now they are not just propaganda, but unethical experiments, as well (Crowley, Richard M. et al. 2025). Manipulation campaigns have shifted from basic bots to now "semi-organic" ones, which involve a coordinated group of human accounts, money-bought influencers, encrypted messaging and AI software. Platform recommendation systems serve as an accelerant, building up environments of information that limit access to differing viewpoints and increase the risk of disinformation. The perimeter of regulation, meanwhile, continues to be incomplete, ambiguous, and unevenly distributed, and much of large-scale cognitive experimentation with populations continues on an unlicensed basis.

1.2. CONCEPTUAL BACKGROUND

It is argued here that shared cognitive influence is not only coordinated, leveraged by technology, and mediated in the beliefs and expectations of a population or identifiable group, but also is characterised by four additional properties: (i) it operates not on individual minds but on the shared epistemic environment (agenda-setting, salience, sentiment), an attribute that is demonstrated empirically by bot-driven steering of aggregate public attention and sentiment 10; (ii) it uses infrastructural levers most notably, algorithmic curation and amplification that narrow the diversity of viewpoints users are exposed to (Schippers, Birgit 2025); (iii) it is typically covert in authorship and intent, which distinguishes it from open advocacy; and (iv) it scales through network effects and semi-organic human-machine campaigns. This paper introduces a normative category, the unsanctioned trial. A deployment of influence technology qualifies if it (a) influences the cognitive environment of a population without the consent of the population; (b) is not subject to ex-ante regulatory approval or independent risk assessment and/or ethical control; and (c) assumes the population's reaction as the result of the experiment. The Cambridge Analytica episode meets all three: the consent was either missing or fabricated for the purpose of data harvesting , operational nature was that of psy-ops and not persuasion , and failures were right in the absence of risk classification, audit and transparency mechanisms that would have removed the intervention ex ante (Zhou, Ke, Šćepanović, Sanja, and Quercia, Daniele 2024). The trial framing reveals that the experimental unit is not the individual, the object of manipulation is not only a transaction or an election, and the enabling condition is not only individual wrongdoing, but the governance gap because trials go on where there is no approval authority. The paper conceptually connects the shared cognitive influence to the human rights framework in terms of the information ecosystem as a precondition for rights enjoyment: rights to information, participation and non-discrimination require a minimally truthful shared environment, and manipulative falsification of that environment harms the rights, even if no statement of specific defamation can be identified(Abrusci, E 2020). It is related to corporate governance by reputation as an information asset whose value relies on the integrity of the same shared environment, and to economic governance, for the market dependence on accurate information that has relevance to price.

2. LITERATURE REVIEW

The baseline comparison is from Bradshaw and Howard's Global Inventory, which reported on organised social media manipulation campaigns in 70 countries, compared with 48 countries and 28 countries of government use in 2018 and 2017, respectively. According to the same inventory, 26 countries have instances of computational propaganda used to silence key human rights, to discredit opponents and to drown out dissent, and countries, including China, Iran, Russia, and Saudi Arabia , are identified as foreign influence operations. Further details are provided on the evolution of tactics in the field. In the interview-based study across 12 countries, Woolley finds that the manipulation campaigns have evolved from relatively simple bot-driven activity to "semi-organic" coordinated human users backfilling AI software and that the abuse of influencers and encrypted messaging has ramped up (Bradshaw, Samantha, and Howard, Philip N. 2019). In strategic-analysis work, influence operations are seen by great powers as a key arena in their competition, alongside the "Firehose of Falsehood," and the cases of Russia, China and Iran, with emphasis on AI-generated content and proxy networks. National-security scholarship now includes the social media platforms as a source of disinformation that can influence perceptions and behaviours, while also connecting micro-level strategies of campaigning to macro-level impacts on social cohesion and institutional trust (Woolley, Samuel 2022). These campaigns are shown to work by means of which can be measured (empirical work). An MIS Quarterly study with ground-truth labels of a bot's social engagement (bot accounts) and real-time clickstream logs

reveals that bot-assisted fake social engagement disproportionately leads public attention to the topic of interest of the bot and even to the specific sentiment attributes the bot wishes to promote. A series of case studies of elections in Romania, Indonesia and Nigeria illustrates how coordinated campaigns, edited videos, fabricated narratives and emotive framing polarise publics, undermine trust in democratic processes and helped lead to the annulment of a presidential first round in Romania (AIONESEI, George Adrian 2026). The microtargeting heart of the argument is provided by the Cambridge Analytica literature. The firm had data about 87 million Facebook users from the personality-quiz app it developed, and the personalities generated from their behaviors were later sold to advertisers who can use "dark post" ads, which can only be seen by targeted users, to exploit their fears. With reference to the 2016 referendum in the UK, Bakir's analysis suggests that Cambridge Analytica's psychographic profiling and targeting was a type of psy-ops because of its deceptive and coercive nature (Dr. Anaukwu, Nneka, and S., Obiozo, Chisom 2025). A process-tracing approach to the same case finds the episode to be the result of a lack of regulation before 2016: the absence of mandatory data-access rights for researchers, the absence of transparency about political advertising, the absence of an ex-ante risk classification of voter-influence systems, and the absence of any audit mechanisms that are presented as independent. There is a specific literature on firms as targets. Experimental studies indicate that when the intent of a fake news is to harm a brand, it is seen as an "organisational crisis" and that the victim must make strategic decisions that correspond to the motivation of the attacker when it comes to disinformation. Research into the corporate misinformation landscape among the S&P 500 shows that targeted companies are less talked about on social media and are subject to more negative comments, lower share price increases and more mention of stress in the workplace. Crisis-communication research indicates some effective rebuttal tactics (e.g., debunking, corrective communication, employee advocacy, influencer partnership, and even "denial by humour"), and suggests that correction messages measurably reduce the level of perceived organisational reputation when compared to the misinformation only condition (Abrusci, E 2020). A reputational-risk strand outlines the connection between the adverse media and viral misinformation causing financial loss, boycotts and regulatory scrutiny, and provides case studies ranging from Deepwater Horizon to Cambridge Analytica to Maggi.In securities and market-integrity literature, the intentional dissemination of false or misleading information is considered a form of market manipulation that can alter the price formation process, harm investors and is subject to civil and criminal liability regimes as deterrents(Oliveira, Rafael S. 2018). Investor-protection scholarship identifies two types of protection: preventive protection (education, disclosure supervision), and repressive protection (litigation, sanctions), and concludes that current regimes are lacking in enforcement.

3. RESEARCH GAP

The influence-operations, human rights, corporate reputation and securities literatures describe the same underlying conduct from four different vantage points, with little integration. No established framework treats a covert influence campaign simultaneously as a rights problem, a reputational externality and a market-integrity event. The psychographic and surveillance-capital literature diagnoses opacity and manipulation, and the human rights literature diagnoses rights impacts, but neither names the deeper structural problem this paper terms the unsanctioned trial: influence technology deployed at population scale without ex-ante approval, informed consent or independent evaluation. The Cambridge Analytica work comes closest, locating the failure in a pre-2016 regulatory vacuum, but does not generalise the finding into a trial-like category.

4. RESEARCH OBJECTIVES

1. To conceptualise shared cognitive influence as a measurable social process (content, amplification, targeting, network dynamics) distinct from ordinary persuasion and advertising.
2. To analyse the corporate reputational stakes, treating firms as targets, instruments and potential beneficiaries of influence operations.
3. To evaluate the economic governance problem: how cognitive manipulation distorts information and price formation, and how regulation interacts with corporate information strategy.

5. RESEARCH QUESTIONS

1. What constitutes shared cognitive influence and by what mechanisms does it operate on collectives rather than individuals?
2. How does targeted disinformation affect corporate reputation and what evidence exists on the effectiveness of corporate responses?
3. How does cognitive manipulation interact with economic governance, in particular market information flows, investor protection and the regulatory instruments states adopt in response?

6. DISCUSSION AND ANALYSIS

The empirical literature confirms that influence operations work on the aggregates: topic attention is not the only thing that can be influenced with the help of bots, but so can be sentiment attributes, in the direction the influence operator wants. This is an aggregate mechanism, which makes it difficult to litigate harms under individualist frameworks. Even though an individual cannot prove a discrete injury resulting from a particular false post, the effect of the false post on the population can be demonstrated. From a doctrinal perspective, the literature on human rights has also come to the same structural conclusion: The harm doctrine should be broadened to include diffuse politico-epistemic harm. The unsanctioned-trial concept provides a common object to both literatures: a trial is just an intervention with a defined harm profile at the population studied level, not the individual level. The corporate evidence suggests that companies have three roles: they are targets (negativity is measurable, they are stock drags, when fake news hits, their employees are stressed); they are instruments (the platforms and ad infrastructure they use host the campaigns; regulation of misinformation definitely alters their social media strategy) and they are operators (companies use persuasion technology themselves; when fake news hits , their employees are stressed. This triple position accounts for the apparent paradox of corporate incentives: they spend a lot of money on crises and at the same time they are against transparency that would make their influence more difficult to perform. The external impact on the economy, therefore, needs to be priced both ways. One of the main discoveries from the literature is that disinformation attacks on rights can also be destabilising for democracy, and that counter-disinformation efforts can have a rights-prejudicial impact, while previous attempts have been found to be insufficient and harmful. This tension is reflected in the design of the DSA: it retains liability exemptions but introduces safeguards, and the critiques highlight safeguards themselves bring accountability and over-removal risks (transparency, trusted flaggers, dispute resolution). Any proposal to the governance of cognitive influence must, therefore, be double-keyed: powerful enough to gate outs the trials that aren't approved, and weak enough to tolerate legitimate expression. Population-scale influence deployments as a means of measuring them, suggests an ex-ante governance framework that is not currently offered by any of the current regimes risk classification prior to deployment, informed-consent or transparency substitutes where informed-consent is not possible, independent audit, and the post-hoc evaluation duties. It was this missing ex-ante layer that Cambridge Analytica's post-mortem revealed, and the risk-based structure of the AI Act is consistent with this being administratively possible for AI systems. The gap is not technical, it is conceptual: none of the regimes to date has developed a concept of campaign and not of tool to classify campaigns according to their risk for a population's epistemic environment.

7. CONCLUSION

Shared cognitive influence is an authentic, measurable, collectively manifested phenomenon with documented mechanisms (bot-amplified agenda and sentiment steering, algorithmic narrowing of viewpoint diversity, semi-organic campaign structures) and documented harms in both elections and crises, in group-targeted discrimination and in flow of market information. The paradigm cases, and the enabling condition for them, the absence of any ex-ante approval, consent or evaluation gate for population scale interventions in cognition, is well captured by the unsanctioned-trial category. The regulatory architecture is substantive but disjointed in slices, with preliminary signs of inconsistent implementation of the platforms by the regulators, AI transparency rules having an unevenly interpreted transparency gap, and the rules on political-advertising being under-resourced for AI manipulation. Firms are at once victim, vector and operator of cognitive influence; this is why the incentive for a firm is inherently unstable and why it makes sense to price the externality both on the defensive side and on the offensive side.

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SOVEREIGNTY, SEA, AND SUSTAINABILITY: AN ENVIRON-LEGAL STUDY OF MARINE GOVERNANCE IN THE INDIAN OCEAN

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Abstract: The Indian Ocean is facing significant climate stressors at the subsurface level such as rapid ocean acidification and deep-sea deoxygenating, but is legally underdeveloped in terms of environmental governance in the region. The need of the hour is filling the research gap on the assessment of the role played by international environmental law in the specific geopolitical context of the Indian Ocean in the Indian region, to the extent that it deals with these concealed environmental crises. Based on a doctrinal approach, this study is an analytical examination of the main legal documents, using the doctrines of Common Heritage of Mankind, Due Diligence and the Precautionary Principle to assess state obligations under UNCLOS and the BBNJ Agreement. The results show that existing measures are not sufficient to effectively implement these principles in order to reduce subsurface heating and acidification, thereby leaving the Indian Ocean's deep-sea ecosystems illegally safeguarded against climate-induced degradation. Finally, binding sub-surface marine environmental justice through regional treaties is crucial for effective and strong climate governance in the fast-warming Indian Ocean region.
Keywords: Indian Ocean, Marine Environmental Governance, Common Heritage of Mankind, UNCLOS, BBNJ Agreement.

1. INTRODUCTION

The ocean is a central component of the Earth's life-support system.
— United Nations, *The Ocean and the Law of the Sea*

The Indian Ocean is the third largest ocean in the world but it has been poorly studied and poorly recognised under the law compared to other ocean areas (Zhang & Wan, 2025). It covers nearly one-third of all the ocean waters, accounts for a significant portion of the world's maritime commerce, and is the habitat of fish and the source of energy resources, as well as fishing and tourism for a coast of twenty-eight littoral states with varying legal structures, development levels and political interests (Salve, 2018). This diversity is a governance issue because it creates "less legal common ground than in places like the Pacific" and makes it difficult to coordinate oceans governance (Techera, 2019).

This sea is under three pressures. First, environmental; "Immense pressure" on the marine environment of the Indian Ocean due to over-exploitation, pollution and degradation of coastal ecosystems, the increasing amount of plastic waste and the oil spills and coral bleaching events revealing the lack of implementation of existing obligations (Patterson et al. 2017; Bennett et al. 2019; UN 2019). Second, developmental; the blue economy is the policy frame that has taken precedence in the region with IORA prioritizing it as a focus area, but not yet managed efficiently, the blue economy could lead to unsustainable environmental impacts, and the ecological costs may become unsustainable if there are cumulative impacts across interconnected ocean areas (Allison et al. 2020). Third, juridical; UNCLOS provides coastal states with broad sovereign rights over maritime areas and imposes upon them the responsibility of protecting and preserving the marine environment, resulting in a tension between unilateral and sovereign assertions and ecological interdependence (Salve, 2018).

1.1.CONCEPT

Marine governance:
Marine governance is the sum of all legal instruments, institutions and processes that help to order human activities in the sea, including fisheries, shipping, energy production, pollution control and biodiversity conservation. The concept is now firmly from sectoral management to integrated ecosystem-based management, where the environmental, social and economic aspects of the ocean are managed as one. UNCLOS provides the constitutional framework of this integration and its two implementation agreements, and SDG-14 calls for full implementation of international law as reflected in UNCLOS as an express commitment of state parties (Bhojwani,2026). The blue economy is the contemporary test-case for the concept: a sustainable use of the oceans for economic development, better livelihoods and jobs, all whilst safeguarding the health of the ocean ecosystem, as the promise of extracting "further wealth from the oceans whilst enhancing environmental protection" depends on good governance quality.

Sovereignty and the sea:
Sea power is organised around three juridical notions. First sovereign territory: territorial sea, within which state sovereignty is plenary. Second is the sovereignty rights, functional jurisdiction over the 200 nm exclusive economic zone and continental shelf, ownership rights over resources but not over the water column, which in India's case are vested in the Union by Article 297 of the Constitution as amended in 1963 and 1976 (Gissi et al. 2022). Thirdly, shared jurisdiction: the high seas and now, under the 2023 BBNJ Agreement, marine biodiversity beyond national jurisdiction, managed as a commons, through area-based management, environmental impact assessment and benefit-sharing (Techera, 2019). The environ-legal notion is that these are not just rights but responsibility-carriers, the same Article 192 duty to protect and preserve the marine environment applies to the state exercising the rights of each zone.

Sustainability principles:
The following words, which were introduced by courts and treaties into the marine governance lexicon, should be kept in mind. the ecosystem approach, which is rooted in the regional-seas logic of UNCLOS Article 123 for enclosed and semi-enclosed seas (Voyer et al. 2021); the polluter pays principle (absolute liability for harm, which extends also to remediation) (Schlüter et al. 2020) and common but differentiated responsibilities from the Rio Declaration, which was explicitly pointed out as being poorly implemented in the Indian Ocean. (Partelow et al.2019)

Marine spatial planning:
MSP is the operational concept that combines the above: a practical tool for developing and structuring the uses of marine space and how they relate to each other; incorporating conservation, sustainable resource use, energy production, shipping and bio-prospecting in a coherent spatial allocation (Kelman, 2020). It reflects the ecosystem approach in, and in the limits of UNCLOS' rules on jurisdiction and is the concept that makes "development space" thinking conformable with good environmental status (Techera, 2019).
The article builds the organizing triad from these elements: sovereignty (the juridical allocation of authority over the sea), the sea (the shared ecological space that is partitioned by jurisdictional lines but cannot be divided), and sustainability (the normative standard against which the exercise of allocated authority is judged).

2. REVIEW OF LITERATURE

- **The legal-vacuum problem.**

Techera notes that though the Indian Ocean is home to nearly one-third of the global oceans and a hub for maritime trade, little legal research has been devoted to the region and no binding instruments exist which cover the entire region, with the exception of IORA, whose membership is comprised of Asian and African states, island and continental states, but which has "limited authority, formal rules and legal structures" (Techera, E. J.,2019). Marine environmental laws in the region have evolved organically, "in different jurisdictions, at multiple levels and in response to different drivers", resulting in a fragmented

picture of the region's laws with rules "scattered across a range of laws, regulations, policy documents and soft law instruments", making implementation difficult and allowing weaker protection in one jurisdiction to cause trans-boundary harm.

- **Sovereignty and UNCLOS.**

Salve's analysis of marine spatial planning will examine how the general obligations of coastal states to prevent, reduce and control pollution, contained in Part XII of UNCLOS (Articles 192-206), are linked to the call for a regional-seas approach, particularly for enclosed and semi-enclosed seas. India's domestic translation of these responsibilities extends the 12 nm territorial sea, the 24 nm contiguous zone and the 200 nm EEZ, as well as boundary settlements with Indonesia, Maldives, Myanmar, Sri Lanka, Thailand and (in 2014) Bangladesh, but not Pakistan.

- **Regional cooperation and its shortcomings.**

According to the “blue community” study by Zhang and Wan, what is more important is that South Asian cooperation is of a “multiple layers, cross-thematic and a mix of soft and hard measures”, with the Article 197 cooperation obligation as its formal foundation and loose networks built on cooperation in fields such as the blue economy and maritime security. However, the regional architecture (SACEP, IORA, IOTC) is "weak in terms of legal integration, capacity building and dispute resolution," during a time that plastic waste, oil spills and coral bleaching have highlighted that obligations under UNCLOS are not being met and that common but differentiated responsibilities are not being realised. Regulatory fragmentation "results in inefficiencies in the effectiveness of marine environmental protection and causes legal incoherence and inconsistent levels of enforcement".

The integration of the blue economy and institutions is discussed by Mishra et al., who redefine the health of the ocean as the economic health through questioning the issue in the context that the degradation of ecosystems is an infrastructure failure, with attendant economic, financial and social risk, and that the core governance problems for India's blue economy lie in fragmented institutional mandates, weak policy integration, and the limited incorporation of ecological risk into financial and planning systems.

2.1.RESEARCH GAP

Despite a complete normative framework (UNCLOS Part XII, MARPOL, CBD, BBNJ) granting and simultaneously binding state sovereignty over the Indian Ocean, marine governance in the region fails in implementation, domestic laws are fragmented across statutes and ministries, regional institutions produce only non-binding soft law and enforcement is uneven across littoral states, so that individually adequate exercises of sovereign authority aggregate into regionally unsustainable outcomes.

2.2.RESEARCH OBJECTIVES

I. To examine the international legal framework (UNCLOS, MARPOL, CBD, BBNJ) governing marine environmental protection in the Indian Ocean region.
II. To analyse how littoral states, with India as the primary case, translate sovereign rights over maritime zones into environmental governance obligations through domestic legislation.
III. To evaluate the coherence and effectiveness of regional institutions (IORA, SACEP, IOTC) in reconciling sovereign autonomy with collective sustainability goals.

2.3. RESEARCH QUESTIONS

I. In what ways is sovereignty and environmental responsibility over Indian Ocean maritime areas divided between international law?
II. How compatible are Indian and South Asian domestic laws with UNCLOS and other environmental related conventions?
III. Can marine spatial planning and the blue economy balance conflicting sovereignty over the same sea space with protection of the ecosystems?

3. RESEARCH METHODOLOGY

The research design used in this study is qualitative, non-empirical, doctrinal legal analysis, and assisted by comparative, case based, and policy analysis. It is the methodological setup which is most similar to the one adopted in the literature, such as in the South Asian marine environmental protection study,

where domestic law is compared and tested to international law, and in the India blue-economy governance study, which is carried out by narrative review of the national policy and institutional framework. The Indian case is contrasted to the other states of the northern Indian Ocean littoral of Pakistan, Bangladesh, Sri Lanka and Maldives, on four measures based on comparative literature, namely legislative completeness, the effectiveness of enforcing the law, policy priorities and long-term challenges. The comparison is not statistical and it does not ignore that the legal environment and socio-cultural context of each individual state will have different reform options.

3.1.INTERNATIONAL MECHANISMS

There are three levels to the international machinery governing the Indian Ocean.
The global constitutional layer: UNCLOS. UNCLOS is like the "constitution for the oceans. Part XII (Articles 192-206) has placed upon the coastal states the responsibility of protecting and preserving the marine environment and taking all measures at their disposal, "individually or jointly", to prevent, reduce and control pollution from all sources together with dumping, vessels, land-based sources, seabed activities and the atmosphere, "using the best practical means at their disposal". Article 197 requires cooperation between States in the formulation of rules and standards on a global and regional level, Article 123 provides for general coordination between States bordering enclosed and semi-enclosed seas and Article 194(5) protects rare and fragile ecosystems. The zonal grant of jurisdiction extends through Article 297 and its land based counterpart such as the Maritime Zones Act, 1976 of India which provides for a 12 nm territorial sea, 24 nm continental shelf and 200 nm EEZ.

Sustainability principles:
The following words, which were introduced by courts and treaties into the marine governance lexicon, should be kept in mind. the ecosystem approach, which is rooted in the regional-seas logic of UNCLOS Article 123 for enclosed and semi-enclosed seas (Grydehoj & Kelman, 2017; Chandler & Pugh, 2020); the polluter pays principle (absolute liability for harm, which extends also to remediation) (Edwards et al. 2019) and common but differentiated responsibilities from the Rio Declaration, which was explicitly pointed out as being poorly implemented in the Indian Ocean (Wu et al, 2020; Zhang & Xiao, 2020).

Marine spatial planning:
MSP is the operational concept that combines the above: a practical tool for developing and structuring the uses of marine space and how they relate to each other; incorporating conservation, sustainable resource use, energy production, shipping and bio-prospecting in a coherent spatial allocation (Suriya, T.,2026). It reflects the ecosystem approach in, and in the limits of, UNCLOS' rules on jurisdiction and is the concept that makes "development space" thinking conformable with good environmental status (Techera, E. ,2023).
The article builds the organizing triad from these elements: sovereignty (the juridical allocation of authority over the sea), the sea (the shared ecological space that is partitioned by jurisdictional lines but cannot be divided), and sustainability (the normative standard against which the exercise of allocated authority is judged).

3.2.NATIONAL MECHANISM

INDIA: India has the region's most complete system: it scores "high" on the legislative completeness and "medium-high (strong judiciary)" on the enforcement effectiveness. The Seventh Schedule, List I (Entries 21, 25-28, 30, 53, 67) lists the Union as competent in the matter of major ports, maritime shipping and navigation, lighthouses, piracy, high-seas crime, regulation and carriage of goods by sea(Zeng, 2016).
The 12 nm territorial sea, 24 nm contiguous zone and 200 nm EEZ are the zones claimed by India and the rights to be exercised in each zone, according to the Territorial Waters, Continental Shelf, Exclusive Economic Zone and Other Maritime Zones Act 1976 which is based on UNCLOS (Techera, E.,2019)
Water (Prevention and Control of Pollution) Act 1974, the very first statute involving the sea, introduced the institution of central and state pollution control boards, with jurisdiction over all waters including the ocean; the Environment (Protection) Act 1986 is a comprehensive framework law which enabled the central government to enact environmental quality standards and pollution-control measures and has

been invoked to issue special notifications relating to marine pollution, coastal development and ecological conservation(Mishra et al., 2026)

The missing link in the structure is integration. India has no single management body for marine affairs at the national level, marine environmental issues are dispersed among ministries and departments of environment, fisheries and shipping and energy, no horizontal coordination platform for marine affairs, and the ambiguity regarding the central–state responsibilities of marine affairs in India results in ineffective local enforcement, especially for the protection of mangroves and prevention of illegal coastal development (Salve, 2018). The Ocean Policy 1982 was well ahead of the time when the concepts of sustainable development, precaution, polluter pays and public trust and the principle of the blue economy became part of ocean-governance lexicon and the literature ends by stating that there is a need to review the old Indian Ocean Policy and a need for an integrated law for the blue economy.

BANGLADESH: Bangladesh has since secured maritime boundary delimitation against India and Myanmar in 2014-15, and in 2021, the Prime Minister's Office put forward a new Blue Economy Development Framework which focuses on cross-sectoral coordination mechanisms, sustainable utilization of marine resources, marine data systems, and enhanced environmental protection (*BELA v. Ministry of Shipping and Others*, 2009). It is rated as having 'medium' legislative completeness, and 'low' effectiveness of enforcement, while population pressure and poverty are rated as its long-term constraints (Bhojwani, 2026).

PAKISTAN: Pakistan's legislative completeness is medium, whereas its enforcement is low, with Federal–Provincial coordination being the main long-term challenge, and its focus on ship-source and industrial pollution.

Sri Lanka: Sri Lanka is rated as "highly specialized" in its legislative system in terms of tourism protection and coral reefs, as well as having medium enforcement, with the challenge of responding to sudden pollution incidents coming out of the woodwork highlighted and answered by the courts in the X-Press Pearl litigation.

MALDIVES. The Maldives is in medium, "highly targeted" legislative system (centred on climate change and waste management); has medium-high enforcement support of manageability; and geographical dispersion, coral bleaching as challenges

4. JUDICIAL DEVELOPMENT

The Supreme Court developed an enviable environmental case law in Article 21. In Vellore Citizens Welfare Forum v. Union of India, the Court adopted the precautionary principle and the polluter pays principle as part of Indian domestic law, imposing absolute liability for environmental damage on the polluter, and including the costs of remediation of the polluted environment. Indian Council for Enviro-Legal Action v. Union of India upheld the polluter pays principle as sound and the Court has continued to invoke both principles via the statutorily created authorities up until 2025. In the shrimp-culture case (S. Jagannath v. Union of India), the notifications of the Coastal Regulation Zone were linked to sustainable development and inter-generational equity. The Supreme Court's ship-breaking line is direct marine, in that it adopted norms binding ship-breakers in Alang based on the report of the expert committee in 2007, which were incorporated into the Ship Breaking Code 2013, and were subsequently enacted as the Recycling of Ships Act 2019, regulating hazardous waste under Basel Convention and oil pollution under MARPOL. In Farooque v. Government of Bangladesh (2001), the Supreme Court determined that a registered environmental association fell under the term "person aggrieved" in Article 102 of the Constitution and thus the public interest litigants had the authority to challenge the pollution of air and water bodies by the industries by invoking the right to a balanced ecosystem. The BELA v. Ministry of Shipping (High Court Division, March 2009) decision is the landmark marine-environment ruling in which it was determined that 36 yards in Chittagong were scrapping end-of-life single hull oil tankers without proper environmental clearance as required by the Basel Convention, and that the government was not properly monitoring decommissioning activities in the marine-environment. The single most important development is the case of MV X-Press Pearl Marine Environmental Pollution (SC/FR 168, 176, 184 and 277/2021, decided July 2025). The Supreme Court determined that the owners, operators and local agents of the vessel were all equally and severally responsible for the disaster, the world's largest marine plastic spill to date, in May-June 2021, and imposed US$1 billion for interim compensation. There are three holdings that are important in marine governance. The polluter pays principle was declared as "absolute and non-negotiable" and there was no defence of non-

negligence. Second, the Court used its fundamental rights jurisdiction (Articles 17 and 126 of the Constitution) which considered marine environmental harm as an infringement on citizens' rights. Third, it discovered that the Attorney General's Department was complicit in the violation itself, for agreeing to proceedings in Singapore rather than the Courts of the Republic, which it described as "unreasonable, irrational and arbitrary". On 13 August 2003, the MV Tasman Spirit grounded in Karachi port, Pakistan's worst marine environmental disaster, spilt approximately 26,000 tonnes of crude oil onto the coast. The constitutional petition (Dr. Amjad H. Bokhari v. Federation of Pakistan, Const. In its argument before the Court (P. 45/2003), it stated that the domestic legal system on marine pollution is weak (with very low fines), fragmented (there are many laws and different sets of responsibilities for state organs) and does not adequately cover accidental and catastrophic spills.

5. DISCUSSION AND ANALYSIS

The evidence across all layers points to one conclusion: sovereignty and sustainability in the Indian Ocean are not rivals but mutually constitutive. UNCLOS grants coastal states dense jurisdiction while binding its exercise, Article 192 and Article 194 obligations attach to the very state exercising each zone's rights. Bangladesh proves the dialectic empirically only after adjudication settled its maritime boundaries against Myanmar and India in 2014–15 could it launch a Blue Economy Development Framework. Environmental obligation is therefore not a limit on sovereignty but its performance standard, sustainability measures are also responsible whether jurisdiction over the sea is exercised legitimately

The region does not lack norms; Part XII, MARPOL, CBD and BBNJ have expanded obligations from controlling single pollutants to protecting ecosystems overall. What it lacks is machinery; regional bodies produce declarations but no binding agreements, and even India's laws are scattered across statutes and ministries with no horizontal coordination platform. This explains the paradox of high legislative completeness coexisting with low enforcement effectiveness across South Asia**.** Regulatory fragmentation produces "legal inconsistencies and inconsistent enforcement standards" precisely where they matter most transboundary pollution control, ecological protection zones and emergency response. Because ocean areas are interconnected and impacts cumulative, weak protection in one jurisdiction generates harm no neighbour's stronger law can undo. The documented incidents, plastic waste, oil spills, coral bleaching, and the largest recorded marine plastic spill in the X-Press Pearl disaster, are the ecological invoice for institutional disunity. Indian constitutional jurisprudence converted international principles into enforceable domestic law like precaution and polluter pays in Vellore Citizens Welfare Forum, affirmed in Indian Council for Enviro-Legal Action, and coastal-zone regulation tied to sustainable development in S. Jagannath. Sri Lanka's X-Press Pearl judgment went further, holding liability "absolute and non-negotiable" and finding the state's own Attorney General's Department in violation of citizens' fundamental rights for declining to prosecute domestically. Two limits temper this: adjudication is reactive, acting after catastrophe rather than before it, and judicial strength is uneven, benefiting India's enforcement rating while Pakistan and Bangladesh's low scores persist. Without effective management, blue economy strategies risk unsustainable impacts and fragmented governance excludes ecological risk from financial and planning systems. Yet treating ocean health as economic infrastructure converts ecosystem degradation into infrastructure failure with cascading economic risk, making conservation a precondition of development. Marine spatial planning is the legal technology for this reframing. India's legislative silence on MSP is not a neutral gap, as the Gulf of Khambhat offshore-wind proposal shows intensifying, conflicting uses will proceed without spatial order unless statute supplies it. Four propositions emerge. First, sovereignty in the Indian Ocean is juridically complete but institutionally uncoordinated, producing systemic unsustainability from individually adequate state action. Second, the normative framework is sufficient; the binding constraint is institutional at national and regional levels. Third, courts have constitutionalised environmental principles but cannot substitute for legislative and administrative integration. Fourth, the blue economy and MSP, properly legislated, are the vehicles reconciling sovereignty and sustainability in practice. The region's governance future depends less on new treaty-making than on the institutional work of making existing obligations enforceable, coherent and spatially planned.

6. CONCLUSION AND SUGGESTIONS

The Indian Ocean's marine governance problem is a mismatch between legal architecture and ecology. Sovereignty has been robustly allocated through UNCLOS and domestic statutes, and adjudication has

even settled rival boundaries, as Bangladesh's successful delimitation cases. Sustainability obligations have been equally robustly declared. What has failed is the connective tissue; fragmented domestic laws, non-binding regional institutions, and uneven enforcement. Because marine ecosystems are interconnected and impacts cumulative, legally partitioned yet institutionally disconnected governance cannot deliver sustainable outcomes. Sustainability is thus the test of responsible sovereignty whether a state's title to the sea is juridically secure, but its legitimacy in exercising that title depends on the health of the marine environment it governs.

Enact a national marine spatial planning statute in India**,** allocating uses across seabed, water column and surface on an ecosystem basis with stakeholder participation and inter-ministerial coordination, giving blue economy investors certainty while embedding environmental protection. Create a unified national marine affairs authority**,** replacing the present four-ministry dispersion with a single coordinating mandate for integrated ocean governance. Harden regional soft law by converting IORA's Blue Economy declarations into regionally binding minimum standards, drawing on the more mature Pacific model of standing organisations and adopted treaties. Strengthen SACEP and IOTC implementation through sustainable core funding and dispute-resolution competence, prerequisites for effective transboundary pollution control. Domesticate the BBNJ Agreement promptly**,** using its four pillars (EIA, area-based management, benefit-sharing, capacity transfer) to align national governance with areas beyond national jurisdiction. Institutionalise the judicial gains by operationalising precaution and polluter pays through standing compensation and restoration mechanisms on the Sri Lankan trust-fund model, and pre-emptive environmental impact assessment rather than post-disaster liability. Clarify central–state responsibilities in coastal enforcement through a cooperative-federalism framework, addressing the unclear division that produces ineffective local enforcement of coastal development controls and mangrove protection.

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ASPECTS OF LEGAL CERTAINTY IN THE TAX REPORTING SYSTEM IN INDONESIA

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ABSTRACT

This study examines the legal certainty aspect in the tax reporting system in Indonesia and the legal consequences that arise if taxpayers do not report their taxes. The Indonesian tax system is faced with various challenges, including regulatory complexity, inconsistent law enforcement, and lack of transparency. These problems have a direct impact on taxpayer compliance and the effectiveness of state revenues. This study uses a normative legal method with an approach to legal theories such as Positive Law (Hans Kelsen), Progressive Law (Satjipto Rahardjo), and Compliance Theory. The results of the study show that although Indonesia has implemented a tax digitalization system such as e-Filing, the success of its implementation still depends on adequate levels of literacy and socialization. Legal uncertainty, especially in enforcement against tax avoidance, weakens public trust in the system. In addition, non-compliance in tax reporting can result in administrative and criminal sanctions, as well as socio-economic impacts, which are examined through the perspective of the theory of justice and utilitarianism. Therefore, there needs to be improvement in regulations, consistency in law enforcement, and ongoing education in order to create a fair, transparent, and efficient tax system.

Keywords: legal certainty, tax reporting, tax sanctions, taxpayer compliance, legal theory

INCREASING PUBLIC PARTICIPATION IN THE IMPLEMENTATION OF LOCAL GOVERNMENT THROUGH THE LOCAL DEMOCRACY STRENGTHENING PROGRAM

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ABSTRACT
This community service activity aims to enhance public understanding and participation in local government administration through a local democracy strengthening program. The activity was conducted in Kutai Kartanegara Regency, involving 60 participants consisting of community members and local stakeholders. The method used was a collaborative approach between the Urban and Regional Planning Study Program (PWK) and the Law Study Program through outreach, focus group discussions (FGD), and participatory interaction. The results of the activity showed an increase in public understanding of the concepts of public participation, transparency, and accountability, with achievements in the high to very high category. Participants' active involvement in discussions also increased, as indicated by the ability to express aspirations and engage in the dialogue process. The interdisciplinary approach applied applied proved effective in providing a more comprehensive understanding of the role of the community in regional development. This activity contributed to strengthening community awareness of the importance of involvement in the planning and supervision of development. Thus, this service program is expected to encourage the realization of a more democratic, transparent, and sustainable regional governance.
Keywords: Community service, Governance, Public participation, Regional democracy, Transparency

INTELLECTUAL PROPERTY GOVERNANCE AND ARTIFICIAL INTELLIGENCE IN A CANDIDATE COUNTRY: LEGAL FRAGMENTATION, REGULATORY GAPS AND EU-ORIENTED POLICY RESPONSES

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Abstract
Digital transformation and artificial intelligence (AI) are profoundly reshaping intellectual property systems, information law, and regulatory governance worldwide. These developments raise complex legal and policy challenges concerning authorship, ownership, data use, platform accountability, privacy, and regulatory enforcement, particularly in countries undergoing legislative harmonisation with the European Union. For North Macedonia, as an EU candidate country, aligning the national legal framework governing intellectual property and information law with the evolving European digital acquis represents both a strategic opportunity for modernisation and a significant regulatory challenge.
This policy paper provides a comprehensive legal and policy analysis of the national regulatory framework governing intellectual property, digital services, personal data protection, cybersecurity, and relevant provisions of criminal law in the context of AI-driven digital transformation. Employing a structured comparative and matrix-based analytical approach, the paper examines the degree of alignment between the principal national legal instruments—including copyright and related rights, industrial property, personal data protection, electronic commerce, electronic identification, network and information security, and selected provisions of the Criminal Code—and the European Union's key digital regulatory instruments, namely the Artificial Intelligence Act (AI Act), the Digital Services Act (DSA), the Digital Single Market (DSM) Directive, the General Data Protection Regulation (GDPR), eIDAS 2.0, and the NIS2 Directive.
The analysis demonstrates that the principal shortcomings of the existing regulatory framework do not arise from the absence of legislation but rather from legal fragmentation, insufficient horizontal coordination, the limited integration of AI-specific regulatory perspectives, and weak institutional implementation capacity. Significant regulatory gaps remain in relation to AI-generated content, text and data mining (TDM), algorithmic transparency, platform governance, the protection of intellectual property in digital environments, and the implementation of data protection principles such as *privacy by design* and *privacy by default* within AI systems.
The policy paper proposes a phased set of legislative and institutional reforms for the period 2026–2028, aimed at strengthening institutional oversight, enhancing regulatory coherence across intellectual property and information law, and establishing a risk-based governance framework aligned with the European Union's evolving digital regulatory architecture. These recommendations are intended to foster innovation, improve legal certainty, safeguard fundamental rights, and support the sustainable development of North Macedonia's digital economy and AI ecosystem.
Keywords: Artificial Intelligence (AI); Digital Transformation; Intellectual Property; Digital Governance; European Union Law; Regulatory Fragmentation; Data Protection; Cybersecurity; Digital Services; North Macedonia.

I. Analysis of the Law on Electronic Commerce and Digital Platforms

Analysis of the Alignment of North Macedonian Legislation with the European Union's Digital Regulatory Framework

Artificial Intelligence Act (AI Act) (EU) 2024/1689, Digital Services Act (DSA) (EU) 2022/2065, and Directive (EU) 2019/790 on Copyright in the Digital Single Market

Introduction

Since obtaining candidate status for membership in the European Union in 2005, the Republic of North Macedonia has pursued the progressive harmonisation of its national legislation with the *acquis communautaire*. Within the field of digital transformation, this process encompasses alignment with the European Union's principal digital regulatory instruments, including the Artificial Intelligence Act (AI Act), the Digital Services Act (DSA), and Directive (EU) 2019/790 on Copyright in the Digital Single Market (DSM Directive). 1

According to the **2025 European Commission Report on North Macedonia**, the country has achieved moderate progress in aligning its digital regulatory framework with the EU acquis. Nevertheless, considerable challenges remain, particularly regarding the implementation of the AI Act and the Digital Services Act, as well as the institutional capacity required for their effective enforcement.

This section focuses on two key legislative instruments governing North Macedonia's digital legal framework:

- the **Law on Electronic Commerce**; and
- the **Law on Electronic Documents, Electronic Identification and Trust Services**.

The analysis evaluates the strengths and weaknesses of these legal instruments in light of the latest European regulatory developments, drawing upon the most recent legislative reforms, European Commission assessments, and relevant policy analyses published in 2025.

1. Law on Electronic Commerce

(*Official Gazette of the Republic of North Macedonia*, No. 135/2022, as amended through 2025)

The Law on Electronic Commerce, originally enacted in 2007 and subsequently amended on several occasions, represents North Macedonia's national transposition of Directive 2000/31/EC on Electronic Commerce. It establishes the legal framework governing electronic commercial transactions, online service providers, electronic contracts, and the liability regime applicable to intermediary service providers.2

As of 2025, the Law is only partially aligned with the European Union's contemporary digital regulatory framework. While certain provisions correspond to the objectives of the Digital Single Market (DSM), the legislation substantially lags behind the requirements introduced by the Digital Services Act (DSA) and the Artificial Intelligence Act (AI Act), primarily because it does not regulate algorithmic transparency, AI risk management, or the responsibilities of very large online platforms (VLOPs).

The Law provides a legal basis for the operation of domestic electronic commerce platforms. However, it does not adequately address the regulatory challenges posed by global digital platforms such as Meta, Amazon, Google, and other multinational online service providers operating within the North Macedonian market.

The legislation defines information society services, regulates the conclusion of electronic contracts, and establishes a limited liability regime for intermediary service providers (Articles 15–20). Nevertheless, because these provisions were adopted prior to the emergence of the DSA and the AI Act, they do not adequately respond to the regulatory challenges created by algorithmic systems, automated content moderation, recommender systems, or very large online platforms.

For example, the **European Commission's 2025 Report** notes that North Macedonia has not yet designated a national Digital Services Coordinator, significantly limiting its capacity to supervise digital platforms with more than 45 million users within the European Union.

Alignment with the European Union Digital Regulatory Framework

Alignment with the Artificial Intelligence Act (AI Act)

The current level of alignment between the Law on Electronic Commerce and the Artificial Intelligence Act remains limited. The legislation does not contain provisions governing the transparency of AI-powered recommender systems, algorithmic accountability, or the risk classification of artificial intelligence applications used in electronic commerce. Consequently, it fails to address several core

1European Commission, North Macedonia Report 2025 (Brussels, 4 November 2025), on accession alignment and the digital transformation acquis.

2Directive 2000/31/EC of the European Parliament and of the Council of 8 June 2000 on certain legal aspects of information society services, in particular electronic commerce, in the Internal Market, OJ L 178, 17 July 2000, pp. 1–16.

obligations introduced by the AI Act, particularly those relating to transparency, risk management, and regulatory oversight of high-risk AI systems.
According to the legal analysis published by **Schoenherr (2024)**, legislative amendments are expected during the forthcoming harmonisation process in order to incorporate the requirements applicable to high-risk AI systems into the national legal framework.

Alignment with the Digital Single Market (DSM) Directive
The transposition of Directive (EU) 2019/790 on Copyright in the Digital Single Market remains only partial. Although the existing legal framework provides a general basis for copyright protection in digital environments, it does not incorporate mechanisms corresponding to Article 17 of the DSM Directive concerning the responsibilities of online content-sharing service providers. 3
In practical terms, this means that online platforms operating in North Macedonia are not subject to explicit legal obligations to verify copyright ownership or obtain appropriate licences before making user-uploaded content publicly available. This regulatory gap may expose both platform operators and users to legal uncertainty, particularly in cross-border situations involving right holders established within the European Union.

Alignment with the Digital Services Act (DSA)
The current framework remains only partially aligned with the Digital Services Act. The European Commission's 2025 assessment expressly states that North Macedonia still needs to align with the DSA. Although domestic legislation contains elements inherited from the earlier e-Commerce Directive model, it does not reproduce the DSA's comprehensive system of due diligence, transparency, systemic-risk and supervisory obligations.4
In particular, the Law does not establish:

- mandatory deadlines for the removal of illegal content;
- procedures for recognising and cooperating with trusted flaggers;
- transparency reporting obligations for online platforms;
- enhanced due diligence requirements for very large online platforms; or
- institutional mechanisms for systemic risk assessment and mitigation.

Accordingly, while the current framework provides a minimum level of legal certainty for electronic commerce, it falls considerably short of the comprehensive governance model established under the Digital Services Act.

Regulatory Gaps
The analysis identifies several structural shortcomings that substantially limit the effectiveness of the current legal framework.
The first concerns the absence of requirements relating to algorithmic transparency. Neither online platforms nor intermediary service providers are required to disclose the operation of recommendation algorithms or automated decision-making systems that may significantly influence consumer behaviour. 5
Secondly, the legislation does not provide for mandatory systemic risk assessments applicable to Very Large Online Platforms (VLOPs), despite the significant influence such platforms exert on digital markets and public discourse. 6
A further weakness lies in the existing enforcement regime. Financial penalties remain relatively low and are unlikely to produce a meaningful deterrent effect. Moreover, the legislation does not establish a national register of digital platforms or a competent authority responsible for their continuous supervision.

3Directive (EU) 2019/790 on copyright and related rights in the Digital Single Market, especially Art. 17 on the use of protected content by online content-sharing service providers.
4European Commission, North Macedonia Report 2025 (Brussels, 2025), section on digital transformation and media; Regulation (EU) 2022/2065 of the European Parliament and of the Council of 19 October 2022 on a Single Market for Digital Services (Digital Services Act), OJ L 277, 27 October 2022.
5Regulation (EU) 2022/2065 (Digital Services Act), Arts. 27 and 38, concerning recommender-system transparency and additional obligations for very large online platforms and search engines.
6Regulation (EU) 2022/2065 (Digital Services Act), Arts. 34–35, requiring VLOPs and VLOSEs to assess and mitigate systemic risks.

The practical consequences of these shortcomings are readily apparent. For example, where fraudulent online advertisements appear on domestic electronic commerce platforms, the current legal framework does not require rapid intervention or impose strict procedural deadlines for removing unlawful content. Such an approach is inconsistent with the obligations established under Articles 16–22 of the Digital Services Act.

Policy Recommendations

To achieve full alignment with the European Union's digital regulatory framework, several legislative and institutional reforms should be prioritised.

Short-term measures (2026)

The Law on Electronic Commerce should be amended to introduce:

- obligations concerning algorithmic transparency;
- a DSA-compatible notice-and-action procedure requiring platforms to process sufficiently precise notices in a timely, diligent, non-arbitrary and objective manner;7
- an effective, proportionate and dissuasive sanctions regime calibrated to the DSA model, under which Member States must provide for maximum fines for non-compliance of up to 6% of the provider's annual worldwide turnover in the preceding financial year.8

Medium-term measures (2027–2028)

Institutional reforms should include:

- the establishment of a National Register of Digital Platforms;
- the designation of a national Digital Services Coordinator;
- specialised training programmes for regulatory authorities, judicial institutions, and online platform operators; and
- the development of institutional capacities for supervising algorithmic systems and digital platforms.

Long-term measures

Following accession to the European Union, North Macedonia should ensure the direct application of the Digital Services Act and the Artificial Intelligence Act, while simultaneously participating in European supervisory structures, including the **European Centre for Algorithmic Transparency (ECAT)**. Such participation would strengthen regulatory cooperation, facilitate knowledge exchange, and improve national capacity for the supervision of AI-enabled digital services. 9

2. Law on Electronic Documents, Electronic Identification and Trust Services

(*Official Gazette of the Republic of North Macedonia*, Nos. 101/2019, 275/2019 and 135/2025)

The **Law on Electronic Documents, Electronic Identification and Trust Services** represents one of the most advanced examples of the harmonisation of North Macedonian legislation with the European Union's digital legal framework. It largely transposes the provisions of the **eIDAS Regulation** (Regulation (EU) No. 910/2014), while the latest amendments adopted in 2025 further align the national framework with **eIDAS 2.0 (Regulation (EU) 2024/1183)**. 10

The Law establishes the legal basis for electronic identification, qualified electronic signatures, electronic seals, electronic time stamps, electronic registered delivery services, website authentication, and other trust services. It also enables the introduction of European Digital Identity Wallets (EUDI Wallets), thereby creating the legal foundations for secure cross-border digital transactions and electronic public services. 11

7Regulation (EU) 2022/2065 (Digital Services Act), Art. 16, establishing the notice-and-action mechanism for illegal content.

8Regulation (EU) 2022/2065 (Digital Services Act), Art. 52(3), providing that the maximum amount of fines for non-compliance may be set at 6% of the annual worldwide turnover of the provider of intermediary services concerned in the preceding financial year.

9Regulation (EU) 2022/2065 (Digital Services Act); Regulation (EU) 2024/1689 (Artificial Intelligence Act). As EU regulations, these instruments are directly applicable in Member States; candidate countries pursue pre-accession alignment with the acquis.

10Regulation (EU) No 910/2014 (eIDAS), as amended by Regulation (EU) 2024/1183 establishing the European Digital Identity Framework.

11Regulation (EU) No 910/2014 (eIDAS), Arts. 3 and 25–45, governing electronic signatures, seals, time stamps, electronic registered delivery services and website authentication; see also Regulation (EU) 2024/1183.

As recognised in the **SMART/MK 2030 Strategy** of the Ministry of Digital Transformation, the 2025 amendments provide a solid legal basis for pilot projects concerning the implementation of the European Digital Identity Wallet and the further development of interoperable digital public services.

Alignment with the Artificial Intelligence Act (AI Act)

Despite its high degree of alignment with the European eIDAS framework, the Law demonstrates only a limited level of compatibility with the Artificial Intelligence Act.

This is particularly evident in relation to biometric electronic identification systems. Under Annex III of the AI Act, biometric identification technologies are classified as **high-risk AI systems**. However, the national legislation does not establish mandatory conformity assessment procedures, CE marking requirements, post-market monitoring obligations, or fundamental rights impact assessments for such systems. 12

Consequently, although the Law effectively regulates electronic identification and trust services, it does not yet address the specific regulatory requirements applicable to AI-enabled biometric technologies.

Alignment with the Digital Single Market (DSM) Directive

The degree of alignment with Directive (EU) 2019/790 on Copyright in the Digital Single Market is partial.

Although the eIDAS framework contributes to the broader objectives of the Digital Single Market by facilitating secure electronic transactions and cross-border digital services, it does not regulate copyright-related aspects associated with digital identity wallets, digital content, or online intellectual property management.

According to the **2025 European Commission Report**, North Macedonia has achieved moderate progress in the development of digital public services; however, greater integration between electronic identification systems and intellectual property protection remains necessary.

Alignment with the Digital Services Act (DSA)

The Law demonstrates a moderate degree of consistency with the Digital Services Act.

Its provisions concerning trust services and secure electronic identification significantly strengthen authentication mechanisms within digital services and electronic transactions. Nevertheless, the legislation does not regulate platform governance, online content moderation, transparency obligations, or systemic risk management, all of which constitute essential components of the DSA framework.

Accordingly, while the Law provides an important technological and legal infrastructure for secure digital services, it cannot be regarded as a substitute for the comprehensive regulatory obligations established under the Digital Services Act.

Regulatory Gaps

The analysis identifies several regulatory shortcomings that require legislative attention.

First, the Law does not establish a risk-classification framework for AI-enabled biometric identification systems. As a result, technologies involving facial recognition, biometric authentication, and other AI-assisted identification methods remain outside the scope of dedicated regulatory supervision.

Secondly, the legislation does not provide for a regulatory sandbox that would enable the controlled testing of innovative digital identity solutions before their large-scale deployment.

A further limitation concerns cross-border recognition. Although qualified electronic signatures enjoy full legal validity within North Macedonia, they are not yet automatically recognised throughout the European Union, thereby creating legal and administrative obstacles for businesses and public institutions engaged in cross-border digital transactions. 13

Finally, the current system of administrative sanctions remains relatively modest and does not yet reflect the enforcement mechanisms envisaged under the latest European regulatory framework.

12Regulation (EU) 2024/1689 (Artificial Intelligence Act), Annex III, point 1, on specified biometric systems classified as high-risk, subject to the scope and exceptions laid down in the Regulation.

13Regulation (EU) No 910/2014 (eIDAS), as amended by Regulation (EU) 2024/1183. Cross-border mutual recognition within the EU framework depends on the Regulation and notified electronic-identification schemes; North Macedonia is not an EU Member State.

Policy Recommendations

To ensure full alignment with the evolving European digital acquis, several legislative and institutional measures should be implemented.

Short-term measures (2026)

The Law should be amended to include:

- a dedicated chapter regulating the use of artificial intelligence in electronic identification;
- mandatory conformity assessment procedures for high-risk biometric AI systems;
- administrative sanctions proportionate to those introduced under the AI Act; and
- fundamental rights impact assessments for AI-enabled identification technologies.

Medium-term measures (2027–2028)

Priority should be given to:

- implementing pilot projects for the European Digital Identity Wallet (EUDI Wallet);
- establishing a national regulatory sandbox for innovative digital identity technologies;
- strengthening institutional capacities through specialised training programmes; and
- enhancing interoperability with European digital identity infrastructures.

Long-term measures

Following accession to the European Union, North Macedonia should ensure the direct application of both the Artificial Intelligence Act and eIDAS 2.0 while actively participating in the relevant European supervisory and cooperation mechanisms. Such integration would significantly strengthen legal certainty, facilitate cross-border digital services, and accelerate the country's digital transformation in accordance with European standards. 14

II. Analysis of Intellectual Property Legislation

1. Introduction

Digital transformation and artificial intelligence (AI) have emerged as key drivers of economic development, technological innovation, and the modernisation of public services. In this context, intellectual property (IP) governance and personal data protection constitute essential components of the legal infrastructure required to achieve an appropriate balance between promoting innovation and safeguarding the rights of creators, innovators, businesses, and citizens.15

This section of the policy paper is based on a comprehensive matrix analysis of three core legislative instruments governing intellectual property and data protection in the Republic of North Macedonia:

- the **Law on Copyright and Related Rights**;
- the **Law on Industrial Property**; and
- the **Law on Personal Data Protection**.

For each legislative instrument, the analysis examines relevant legal provisions, their significance for digital transformation, the degree of alignment with the European Union's regulatory framework—including the Artificial Intelligence Act (AI Act), the Digital Services Act (DSA), the Digital Single Market (DSM) Directive, and the General Data Protection Regulation (GDPR)—as well as their implications for digital services and AI systems. Particular attention is devoted to identifying legislative gaps, implementation challenges, regulatory risks, and policy recommendations, classified according to their level of priority.

The primary objective of this analysis is to provide a comprehensive assessment of the current legal framework, identify its principal regulatory shortcomings, and propose targeted reforms capable of supporting North Macedonia's digital transformation and the responsible development of artificial intelligence in accordance with European standards.

14Regulation (EU) 2024/1689 (Artificial Intelligence Act); Regulation (EU) 2024/1183 (European Digital Identity Framework).

15World Intellectual Property Organization (WIPO), WIPO Technology Trends 2019: Artificial Intelligence (Geneva: WIPO, 2019); WIPO, Revised Issues Paper on Intellectual Property Policy and Artificial Intelligence, WIPO/IP/AI/2/GE/20/1 REV (2020).

2. Methodology and Analytical Framework

The analysis is based upon a structured legal and policy assessment employing a matrix-based methodology designed to evaluate the interaction between national legislation and the European Union's evolving digital regulatory framework.

The methodological approach comprises five interconnected stages:

- a systematic examination of the relevant provisions contained in the three principal legislative instruments;
- a comparative assessment of these provisions against four major European regulatory pillars—the Artificial Intelligence Act (AI Act), the Digital Services Act (DSA), Directive (EU) 2019/790 on Copyright in the Digital Single Market (DSM Directive), and the General Data Protection Regulation (GDPR);
- an evaluation of the digital implications of each legislative provision, including its relevance for software, digital platforms, databases, user interfaces (UI), user experience (UX), electronic public services, and AI systems;
- an assessment of the strategic importance of each provision for digital governance and artificial intelligence; and
- the identification of legislative gaps, implementation risks, and priority policy recommendations.

Unlike a conventional legal analysis, the matrix methodology adopted in this policy paper enables the evaluation of legal provisions according to their practical impact on the digital economy, innovation ecosystems, and electronic public administration. Consequently, the analysis combines doctrinal legal research with a public policy perspective, thereby providing a broader understanding of the effectiveness of the existing regulatory framework.

3. Key Findings by Legislative Instrument

3.1. Law on Copyright and Related Rights

The analysis demonstrates that the **Law on Copyright and Related Rights** constitutes one of the most significant legislative instruments supporting digital transformation in North Macedonia.

Several provisions—including Articles 1–5, 12, 26–38, 51–54, 63–74, as well as those governing collective rights management and the electronic registration system for broadcasting organisations (Articles 135-a to 135-g)—provide an important legal foundation for the protection, licensing, and exploitation of digital creative content.

Strengths

The analysis identifies several positive features of the existing legislative framework.

Computer programs and databases are explicitly recognised as copyright-protected works under Article 12, thereby providing an adequate legal basis for the protection of software and digital databases. 16

The exclusive economic rights granted to copyright holders—including reproduction, communication to the public, and making works available online—extend to digital and online forms of exploitation, ensuring that traditional copyright principles remain applicable within digital environments. 17

Furthermore, the Law provides exceptions and limitations for educational, research, and library activities, thereby facilitating socially beneficial uses of copyrighted works while maintaining an appropriate balance between public and private interests.

An additional positive development is the establishment of an electronic record-keeping system for broadcasting organisations, representing an important step towards the digitalisation of copyright administration and collective rights management.

Regulatory Gaps and Policy Recommendations

Despite the strengths of the existing legislative framework, the analysis identifies several significant regulatory shortcomings that limit its effectiveness in responding to the challenges posed by digital transformation and artificial intelligence.

16Republic of North Macedonia, Law on Copyright and Related Rights, Official Gazette No. 115/2010, as subsequently amended, including Official Gazette No. 87/2025.

17Republic of North Macedonia, Law on Copyright and Related Rights, Arts. 26–38 on economic rights; see also Directive (EU) 2019/790 on copyright and related rights in the Digital Single Market.

AI-Generated Content and Text and Data Mining (TDM)

One of the most significant legislative deficiencies concerns the treatment of AI-generated content and Text and Data Mining (TDM). The DSM Directive expressly regulates TDM through Articles 3 and 4, making this an important benchmark for national copyright reform in the context of AI training.[18] [19]

Although the Law recognises software and databases as copyright-protected works, it does not address the legal status of works created wholly or partially through artificial intelligence, nor does it regulate the use of copyrighted materials for the training of AI models through text and data mining techniques. [20]

Because contemporary AI development frequently relies on large-scale computational analysis of text, images and other data, uncertainty over TDM exceptions, rights reservations and licensing conditions can materially affect technology companies, research institutions, universities and public authorities engaged in AI development.[21]

Policy Recommendation (High Priority)

The Law should be amended to introduce explicit provisions governing AI-generated content and Text and Data Mining, ensuring consistency with evolving European legislation and international best practices. Such reforms should clarify issues relating to authorship, ownership, licensing, and the lawful use of copyrighted works for AI training purposes.

Partial Alignment with the DSM Directive

Although the current copyright framework incorporates the traditional exclusive economic rights of authors, it has not yet been fully adapted to the regulatory model established by Directive (EU) 2019/790 on Copyright in the Digital Single Market. [22]

In particular, the legislation does not comprehensively regulate the responsibilities of online content-sharing service providers, digital platforms, and intermediary services operating within increasingly complex digital ecosystems. [23]

As a consequence, considerable legal uncertainty persists regarding the obligations of online platforms, streaming services, educational platforms, and other providers of digital content.

Policy Recommendation (High Priority)

North Macedonia should complete the transposition of the DSM Directive by introducing comprehensive provisions governing online platforms, intermediary liability, digital licensing mechanisms, and the protection of user-generated content within digital environments.

Recognition of Emerging Digital Content and Open Licensing Models

Another significant regulatory gap concerns the absence of provisions addressing emerging forms of digital creativity and contemporary licensing practices.

The existing Law does not explicitly recognise:

- User-Generated Content (UGC);
- interactive digital platforms;
- dynamic databases;
- collaborative digital environments; or
- open licensing frameworks such as Creative Commons.

18Directive (EU) 2019/790 of the European Parliament and of the Council of 17 April 2019 on copyright and related rights in the Digital Single Market, OJ L 130, 17 May 2019, Arts. 3–4.

19Directive (EU) 2019/790, Arts. 3–4, establishing text-and-data-mining exceptions for scientific research organisations and cultural heritage institutions and a broader TDM exception subject to rights reservation.

20World Intellectual Property Organization, Revised Issues Paper on Intellectual Property Policy and Artificial Intelligence, WIPO/IP/AI/2/GE/20/1 REV (2020); M. Senftleben, "Copyright and AI training data—transparency to the rescue?", Journal of Intellectual Property Law & Practice 20(3) (2025): 182–193.

21See Directive (EU) 2019/790, Arts. 3–4; Martin Senftleben, "Copyright and AI Training Data—Transparency to the Rescue?", Journal of Intellectual Property Law & Practice 20, no. 3 (2025): 182–193.

22Directive (EU) 2019/790 on copyright and related rights in the Digital Single Market, including Arts. 3–4 (TDM) and Art. 17 (online content-sharing service providers).

23Directive (EU) 2019/790, Art. 17; European Commission, North Macedonia Report 2025, Chapter 7, identifying continued need for alignment of copyright legislation with the DSM acquis.

These models have become integral components of the contemporary digital economy and are widely used within higher education, scientific research, public administration, and the creative industries.
The lack of explicit legal recognition creates discrepancies between legal regulation and technological reality, generating uncertainty for universities, research institutions, innovative enterprises, and public-sector digital projects.

Policy Recommendation (High Priority)
The legislative framework should be expanded to recognise open licensing mechanisms, collaborative digital content, and contemporary models of digital rights management. Particular attention should be devoted to publicly funded research outputs and educational resources, where open-access licensing has become an established international practice.

Collective Rights Management in the Digital Environment
The current system of collective rights management represents an important mechanism for protecting copyright in traditional media sectors. However, it remains insufficiently adapted to the realities of digital content distribution.
Existing licensing models lack transparency with respect to online platforms, streaming services, and emerging digital business models. Consequently, both right holders and digital service providers may encounter legal uncertainty regarding licensing conditions, royalty structures, and the administration of digital rights.

Policy Recommendation (High Priority)
The electronic rights management system currently applicable to broadcasting organisations should be expanded to encompass online streaming platforms, digital content-sharing services, and other providers operating within the digital economy. Such reforms would significantly improve transparency, facilitate licensing procedures, and enhance the protection of copyright within digital environments.

Interim Conclusion
The analysis demonstrates that the **Law on Copyright and Related Rights** provides a solid legal foundation for the protection of intellectual property within digital environments. Nevertheless, it remains largely based on legal concepts developed prior to the emergence of generative artificial intelligence, algorithmic content creation, and platform-based digital ecosystems.
Future legislative reform should therefore move beyond traditional copyright protection and adopt an integrated regulatory approach capable of addressing AI-generated content, digital platforms, algorithmic technologies, and emerging models of digital innovation. Such an approach would strengthen legal certainty, promote technological development, and ensure closer alignment with the European Union's evolving digital acquis.

3.2. Law on Industrial Property
The **Law on Industrial Property** constitutes the principal legislative framework governing patents, industrial designs, trademarks, geographical indications, and other industrial property rights in the Republic of North Macedonia. The matrix analysis demonstrates that, although the Law is formally aligned with the core principles of European and international intellectual property law, its regulatory framework has not kept pace with recent technological developments associated with digital transformation and artificial intelligence. 24
Overall, the legislation provides a stable legal basis for the protection of industrial property rights. However, several provisions require substantial modernisation to respond effectively to AI-driven innovation, digital products, software-based inventions, and emerging digital business models.

Strengths
The existing legislative framework demonstrates several important strengths.

24Republic of North Macedonia, Law on Industrial Property, as amended.

First, the legal definitions of industrial property rights and the categories of protected subject matter are largely consistent with international intellectual property standards, including the **Paris Convention**, the **TRIPS Agreement**, and the relevant European Union legal framework. 25

Secondly, the State Office of Industrial Property has already introduced electronic registers and an electronic official gazette, contributing to the digitalisation of administrative procedures and improving public access to industrial property information.

The Law also enables the electronic filing of applications for patents, industrial designs, and trademarks, thereby facilitating more efficient administrative procedures for applicants and reducing procedural barriers.

Furthermore, the statutory requirements governing patentability—including novelty, inventive step, and industrial applicability—are broadly harmonised with the **European Patent Convention (EPC)**, providing legal certainty for inventors and businesses operating within both domestic and European innovation systems. 26

Regulatory Gaps

AI-Related Inventions and Software Innovation

One of the most significant shortcomings concerns the absence of specific guidance regarding software-related inventions and inventions involving artificial intelligence.

Although software-based inventions may, under certain circumstances, satisfy the legal requirements for patent protection when they provide a technical contribution, the current legislative framework offers no practical guidance regarding the patentability of machine learning systems, neural networks, AI-assisted simulations, or other emerging computational technologies.

As a result, inventors, research institutions, universities, and innovative enterprises frequently encounter uncertainty regarding the availability and scope of patent protection for AI-based inventions. 27

Policy Recommendation (High Priority)

National guidelines should be developed to clarify the patentability of software-related and AI-assisted inventions in accordance with the practice of the **European Patent Office (EPO)**. Such guidance would promote legal certainty, encourage innovation, and facilitate technology transfer.

Protection of User Interfaces (UI), User Experience (UX), and Digital Products

A further regulatory deficiency concerns the protection of digital interfaces and virtual products.

The provisions governing industrial designs do not explicitly recognise graphical user interfaces (GUIs), user experience (UX) design, virtual products, or other digital design elements, despite the growing importance of these assets within the digital economy and their increasing recognition under European intellectual property practice.

Consequently, innovative digital products developed by North Macedonian companies, universities, and technology start-ups may not benefit from an adequate level of legal protection.

Policy Recommendation (High Priority)

The Law should expressly recognise graphical user interfaces, digital interfaces, virtual products, and other digital design elements as eligible subject matter for industrial design protection, consistent with evolving European Union practice and the jurisprudence of the European Union Intellectual Property Office (EUIPO). 28

Trademark Protection in the Digital Environment

25Paris Convention for the Protection of Industrial Property; Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS); European Patent Convention (EPC).

26European Patent Convention, Arts. 52–57, setting out patentable inventions and the core requirements of novelty, inventive step and industrial applicability.

27World Intellectual Property Organization, WIPO Technology Trends 2019: Artificial Intelligence (Geneva: WIPO, 2019); see also European Patent Office practice on computer-implemented inventions and artificial intelligence.

28European Union Intellectual Property Office practice on registered designs provides the relevant comparative EU context for graphical user interfaces and other digital design elements.

The current trademark framework does not adequately address several forms of digital trademark infringement that have become increasingly prevalent within online environments.
In particular, the legislation contains no explicit provisions concerning:

- cybersquatting;
- unauthorised use of trademarks on social media platforms;
- trademark infringement through domain names; or
- misuse of trademarks in online marketplaces and digital advertising.

These regulatory omissions reduce the effectiveness of trademark protection in the contemporary digital marketplace and create additional risks for businesses operating online.

Policy Recommendation (Medium to High Priority)
The legislative framework should be expanded to include specialised mechanisms addressing online trademark infringement, cybersquatting, and domain-name disputes, while promoting alternative dispute resolution procedures consistent with the Digital Services Act and relevant European Union legislation.

Open Data and Digital Registers
Although the State Office of Industrial Property maintains electronic registers, these databases remain relatively limited from the perspective of digital innovation and data accessibility.
The current system does not provide: 29

- application programming interfaces (APIs);
- machine-readable datasets;
- advanced search functionalities; or
- open-data services capable of supporting research, innovation, and evidence-based policymaking.

Consequently, researchers, start-ups, technology developers, and public institutions are unable to make full use of industrial property data for analytical and innovation purposes.

Policy Recommendation (Medium to High Priority)
A comprehensive open-data policy should be introduced for industrial property registers. This policy should provide publicly accessible machine-readable datasets, API services, advanced analytical tools, and enhanced interoperability with European intellectual property databases. Such reforms would improve transparency, stimulate innovation, and strengthen evidence-based policymaking.

Interim Conclusion 30
The analysis demonstrates that the **Law on Industrial Property** provides a sound legal basis for the protection of patents, industrial designs, trademarks, and other industrial property rights. Nevertheless, the existing framework has not yet fully adapted to the realities of the digital economy, artificial intelligence, and software-driven innovation.
Future legislative reforms should therefore prioritise the regulation of AI-related inventions, digital interfaces, software innovation, online trademark protection, and open-data governance. Such measures would strengthen legal certainty, improve the competitiveness of North Macedonian innovators, and ensure closer alignment with the European Union's evolving intellectual property framework.

3.3. Law on Personal Data Protection

The **Law on Personal Data Protection** constitutes one of the central pillars of North Macedonia's digital regulatory framework. Largely aligned with the **General Data Protection Regulation (GDPR)**, it establishes the legal principles governing the processing of personal data and provides the institutional foundation for protecting fundamental rights in the digital environment.
The matrix analysis demonstrates that the Law incorporates the principal GDPR concepts, including the fundamental principles of personal data processing, the rights of data subjects, the obligations of controllers and processors, Data Protection Impact Assessments (DPIAs), the appointment of Data Protection Officers (DPOs), and the supervisory role of the Personal Data Protection Agency.

29Authors' matrix-based assessment of the accessibility and functionality of national industrial-property registers; see Republic of North Macedonia, Law on Industrial Property, as amended.
30Authors' synthesis based on the preceding matrix analysis of the Law on Industrial Property and the identified digital-governance gaps.

Consequently, it provides a modern legal framework capable of supporting digital transformation while safeguarding individual privacy rights.

Strengths

The existing legislative framework demonstrates a high degree of formal compliance with the GDPR.

The Law clearly defines the fundamental principles governing the lawful processing of personal data, including lawfulness, fairness, transparency, purpose limitation, data minimisation, accuracy, storage limitation, integrity, confidentiality, and accountability. These principles establish a comprehensive legal foundation for the protection of personal data within both the public and private sectors.

The legislation further requires the appointment of **Data Protection Officers (DPOs)** in appropriate circumstances, mandates the preparation of **Data Protection Impact Assessments (DPIAs)** for high-risk processing operations, and requires controllers and processors to implement appropriate technical and organisational measures designed to ensure data security. 31

An additional strength lies in the institutional role assigned to the **Personal Data Protection Agency**, which operates as an independent supervisory authority broadly consistent with the European model of data protection governance.

Finally, the Law provides for administrative sanctions modelled upon the GDPR enforcement regime, thereby creating an effective legal basis for ensuring compliance and promoting preventive data protection practices.

Regulatory Gaps

The Gap Between Legal Compliance and Practical Implementation

Although formal legislative alignment is substantial, effective protection ultimately depends on implementation, supervisory capacity and the integration of data-protection requirements into system design. This implementation dimension is especially important for AI models, where questions of lawful basis, anonymity, legitimate interests and the consequences of unlawfully processed personal data remain central.32

Many public institutions and private organisations continue to experience difficulties in effectively applying the core principles of data protection within the design, development, and operation of digital systems. Compliance frequently remains procedural rather than substantive, resulting in what is commonly described as **"tick-box compliance."** 33

Consequently, the existence of comprehensive legislation does not necessarily guarantee the effective protection of personal data in practice.

Policy Recommendation (High Priority)

Institutional capacity-building should become a strategic priority through specialised training programmes, practical implementation guidelines, and continuous monitoring of compliance. Particular attention should be devoted to strengthening organisational accountability and integrating data protection requirements into everyday administrative and business processes.

Limited Implementation of *Privacy by Design* and Data Protection Impact Assessments (DPIAs)

A further challenge concerns the limited practical application of the principles of **privacy by design** and **privacy by default**.

Although the Law formally requires Data Protection Impact Assessments in situations involving high-risk processing activities, such assessments are often undertaken only as a formal legal obligation rather than as an integral component of system design and risk management. Similarly, privacy considerations

31Regulation (EU) 2016/679 (GDPR), Arts. 35–37, on data protection impact assessments and data protection officers.

32Regulation (EU) 2016/679 (General Data Protection Regulation), in particular Arts. 5, 6, 25 and 35; European Data Protection Board, Opinion 28/2024 on Certain Data Protection Aspects Related to the Processing of Personal Data in the Context of AI Models, 18 December 2024.

33Authors' implementation assessment; compare European Commission, North Macedonia Report 2025, on institutional capacity and implementation challenges in digital transformation.

are rarely incorporated at the earliest stages of developing digital public services or artificial intelligence systems. 34

This situation increases the likelihood of data breaches, security incidents, violations of individual privacy, and diminished public trust in digital services.

Policy Recommendation (High Priority)

The preparation of Data Protection Impact Assessments should become a mandatory prerequisite for all major digital transformation projects and AI systems financed through public funds or European Union programmes. Standardised DPIA templates and sector-specific implementation guidelines should also be developed to promote consistent practice across institutions.

Limited Digital Support for the Exercise of Data Subject Rights

The Law grants data subjects a broad range of rights, including the rights of access, rectification, erasure, restriction of processing, data portability, and objection.

However, the digital infrastructure required to facilitate the practical exercise of these rights remains insufficiently developed. National portals, online forms, digital dashboards, and other electronic interfaces frequently fail to provide user-friendly mechanisms through which individuals may exercise their rights efficiently.

As a consequence, many citizens continue to rely upon traditional paper-based procedures, reducing both the accessibility and effectiveness of digital public services.

Policy Recommendation (High Priority)

National digital platforms should incorporate harmonised user experience (UX) standards specifically designed to facilitate the exercise of data subject rights through secure, accessible, and user-centred digital interfaces. Improving usability would strengthen public confidence in electronic services while enhancing compliance with European data protection standards.

Institutional Capacity of the Personal Data Protection Agency

The Personal Data Protection Agency plays a central role in supervising compliance with the national data protection framework. Nevertheless, its operational effectiveness is constrained by limited human, financial, and technological resources.

These institutional limitations reduce the Agency's capacity to conduct proactive supervision, monitor increasingly complex AI-based processing operations, and provide timely guidance to public authorities and private organisations.

Policy Recommendation (High Priority)

The institutional capacities of the Agency should be strengthened through increased investment in specialised personnel, digital infrastructure, advanced supervisory technologies, and continuous professional training. Strategic priorities should also be established for the supervision of artificial intelligence, algorithmic decision-making, and emerging digital technologies.

Administrative Sanctions

Although the Law establishes an administrative sanctions regime broadly modelled upon the GDPR, the analysis indicates that the practical criteria governing the imposition of sanctions remain insufficiently transparent.

The absence of clear enforcement guidelines may result in inconsistent decision-making and reduced legal certainty for both public authorities and private organisations.

Policy Recommendation (High Priority)

Transparent enforcement criteria and practical guidance should be developed to ensure that administrative sanctions are applied consistently, proportionately, and predictably. Greater emphasis should be placed on preventive supervision, regulatory guidance, and compliance assistance prior to the imposition of financial penalties.

34Regulation (EU) 2016/679 (GDPR), Arts. 25 and 35, on data protection by design and by default and data protection impact assessments.

Interim Conclusion

The analysis demonstrates that the **Law on Personal Data Protection** is among the most highly harmonised components of North Macedonia's digital legal framework. Nevertheless, effective data protection depends not only upon legislative alignment with the GDPR but also upon robust institutional capacity, practical implementation, and a culture of compliance.

Future reforms should therefore prioritise strengthening institutional effectiveness, embedding *privacy by design*throughout the digital transformation process, enhancing the practical exercise of data subject rights, and preparing the national data protection system for the regulatory challenges associated with artificial intelligence and other emerging digital technologies. Such measures would contribute significantly to improving legal certainty, reinforcing public trust, and supporting the sustainable development of North Macedonia's digital ecosystem.

4. Cross-Cutting Digital Implications and Regulatory Risks

The matrix analysis reveals several structural challenges that recur across the different legislative instruments examined in this policy paper. Rather than representing isolated regulatory shortcomings, these challenges reflect systemic weaknesses that undermine the coherence and effectiveness of North Macedonia's digital legal framework.

Although the individual laws regulate different areas of digital governance, they collectively demonstrate similar patterns of legal fragmentation, limited institutional coordination, and insufficient preparedness for the challenges associated with artificial intelligence and the digital economy. These cross-cutting deficiencies significantly reduce the overall effectiveness of the regulatory system and impede the country's alignment with the evolving European Union digital acquis.

4.1. Regulatory Fragmentation

One of the principal findings of this policy analysis is the existence of significant regulatory fragmentation across the national legal framework.

Copyright law, industrial property law, personal data protection, electronic commerce, cybersecurity, and digital governance continue to operate as largely independent legal regimes. In practice, however, contemporary digital products and AI-based services integrate software, data, digital content, industrial designs, trademarks, and personal data into complex and interconnected technological ecosystems.

This mismatch between technological reality and legal regulation creates overlapping competences, inconsistencies in regulatory approaches, and legal uncertainty for businesses, public institutions, researchers, and technology developers.

Accordingly, future legislative reforms should prioritise horizontal regulatory integration rather than isolated amendments to individual statutes. A coherent digital governance framework requires greater coordination among legal disciplines and stronger institutional cooperation across competent authorities.

4.2. Limited Integration of Artificial Intelligence within Intellectual Property Legislation

The analysis further demonstrates that none of the principal intellectual property laws explicitly recognises artificial intelligence as a distinct regulatory subject.

Current legislation addresses AI only indirectly through provisions relating to software, databases, or high-risk data processing activities. Consequently, fundamental legal questions concerning AI-generated content, machine learning, automated creativity, algorithmic innovation, and ownership of AI-assisted outputs remain largely unresolved.

This legislative gap creates considerable uncertainty regarding authorship, ownership, licensing, liability, and the commercial exploitation of AI-generated works and technological innovations.

Given the rapid evolution of artificial intelligence technologies, integrating AI-specific regulatory provisions into intellectual property legislation should constitute a strategic legislative priority. Such reforms would provide greater legal certainty while promoting innovation and technological competitiveness.

4.3. Insufficient Digital Standards for Electronic Services

Although several legislative instruments provide for electronic registers, online administrative procedures, and digital public services, the overall level of digital maturity remains relatively limited.

The analysis identifies shortcomings in:

- interoperability between public information systems;
- usability of electronic services;
- accessibility of digital public platforms;
- availability of open-data resources; and
- integration of digital identity solutions across public institutions.

As a consequence, many electronic services remain fragmented, technologically outdated, or insufficiently user-oriented, thereby reducing both administrative efficiency and public trust.

Future reforms should therefore promote user-centred digital public services supported by interoperable information systems, common technical standards, and secure digital infrastructures consistent with European interoperability principles.

4.4. Limited Support for Innovative Digital Business Models

The current legislative framework provides only limited support for emerging digital business models and innovation ecosystems.

Several important areas remain insufficiently regulated, including:

- Text and Data Mining (TDM);
- AI-generated content;
- protection of graphical user interfaces (GUIs) and user experience (UX) design;
- online trademark enforcement;
- platform governance; and
- digital licensing mechanisms.

These regulatory gaps create uncertainty for start-ups, small and medium-sized enterprises (SMEs), universities, research institutions, and technology developers seeking to commercialise innovative digital products and services.

A modern digital economy requires legislation capable of accommodating rapid technological change while providing predictable legal rules that encourage investment, research, entrepreneurship, and cross-border digital cooperation. 35

Interim Conclusion

The cross-cutting analysis demonstrates that the principal weaknesses of North Macedonia's digital regulatory framework are structural rather than sector-specific. Although substantial legislative progress has been achieved in individual policy areas, the absence of an integrated governance model continues to hinder the effective regulation of digital transformation and artificial intelligence.

Addressing these challenges requires more than incremental legislative amendments. It calls for a comprehensive regulatory strategy capable of integrating intellectual property, digital services, personal data protection, cybersecurity, and artificial intelligence into a coherent and future-oriented legal framework. Such an approach would not only strengthen legal certainty and institutional effectiveness but also enhance North Macedonia's capacity to participate fully in the European Digital Single Market and to support sustainable digital innovation.

5. Strategic Policy Recommendations

The findings of this policy paper demonstrate that strengthening North Macedonia's digital legal framework requires a coordinated programme of legislative reform, institutional capacity-building, and strategic policy development. Rather than relying on isolated amendments to individual laws, future reforms should adopt an integrated governance approach capable of addressing the legal, technological, and institutional challenges arising from digital transformation and artificial intelligence.

To facilitate a gradual and sustainable transition towards a modern regulatory framework aligned with the European Union's digital acquis, the proposed measures are organised into short-term, medium-term, and long-term priorities.

5.1. Short-Term Priorities (High Priority)

35WIPO, WIPO Technology Trends 2019: Artificial Intelligence (Geneva: WIPO, 2019), discussing the relationship between AI-related technological development, intellectual property and innovation ecosystems.

Revision of the Law on Copyright and Related Rights

The first legislative priority should be the comprehensive revision of the Law on Copyright and Related Rights.

The amended legislation should introduce explicit provisions regulating **Text and Data Mining (TDM)**, AI-generated content, and the legal status of works produced with the assistance of artificial intelligence. Furthermore, the national copyright framework should be fully aligned with Directive (EU) 2019/790 on Copyright in the Digital Single Market, particularly regarding the responsibilities of online platforms, intermediary service providers, and digital content-sharing services.

Such reforms would significantly improve legal certainty for authors, technology developers, research institutions, universities, and digital businesses operating within AI-driven environments.

Strengthening Privacy by Design and Data Protection Impact Assessments

The second immediate priority concerns the systematic implementation of the principles of **privacy by design** and **privacy by default** across all public-sector digital transformation initiatives. 36

Data Protection Impact Assessments (DPIAs) should become a mandatory prerequisite for all large-scale digital projects and AI systems financed through national or European Union funding programmes. Standardised methodologies and practical guidance should accompany these requirements to ensure their consistent application across institutions. 37

Embedding privacy considerations into the earliest stages of system design will strengthen legal compliance, reduce operational risks, and enhance public trust in digital public services.

National Guidelines for AI and Software-Related Inventions

A further short-term priority should be the preparation of national guidelines governing the protection of software-related inventions and AI-assisted innovations.

These guidelines should be developed in cooperation with the **European Patent Office (EPO)** and should provide practical clarification regarding patentability requirements, AI-assisted inventions, software innovations, machine-learning technologies, and digital products.

Greater legal certainty in this area would encourage research, innovation, technology transfer, and commercialisation of advanced digital solutions developed by universities, research centres, and private enterprises.

5.2. Medium-Term Priorities

Development of a National Strategy on Intellectual Property and Artificial Intelligence

The analysis indicates the need for a comprehensive National Strategy integrating intellectual property, digital transformation, and artificial intelligence.

Such a strategy should establish common policy objectives, define institutional responsibilities, coordinate legislative reforms, and promote cooperation among public institutions, academia, industry, and civil society.

Rather than addressing individual legal sectors separately, the Strategy should provide a unified governance framework capable of responding to the multidisciplinary nature of contemporary digital ecosystems.

Establishment of a National Coordination Mechanism

The Government should establish a permanent interinstitutional coordination body responsible for issues relating to intellectual property, digital governance, cybersecurity, artificial intelligence, and emerging technologies.

This body should facilitate cooperation among ministries, regulatory authorities, supervisory agencies, universities, research institutions, and representatives of the private sector. It should also monitor legislative developments within the European Union and coordinate the gradual alignment of national legislation with the evolving digital acquis.

36Regulation (EU) 2016/679 (GDPR), Art. 25, requiring data protection by design and by default.

37Regulation (EU) 2016/679 (GDPR), Art. 35; European Data Protection Board, Opinion 28/2024 on certain data protection aspects related to the processing of personal data in the context of AI models (18 December 2024).

Strengthened institutional coordination would substantially reduce regulatory fragmentation and improve policy coherence across the digital governance framework.

Support for Universities and Public Research Institutions

Universities and publicly funded research organisations should receive institutional support in developing comprehensive intellectual property policies addressing ownership, management, licensing, and commercialisation of software, databases, graphical user interfaces, digital platforms, and other research outputs generated through publicly funded projects.

Clear institutional policies would encourage innovation, facilitate technology transfer, strengthen university–industry cooperation, and improve the commercial exploitation of publicly funded research.

5.3. Long-Term Priorities

Full Alignment with the Artificial Intelligence Act

As part of progressive harmonisation with the European Union acquis, North Macedonia should prepare for substantive alignment with the Artificial Intelligence Act and the institutional arrangements necessary for its effective application.38 39

Particular attention should be devoted to:

- governance of high-risk AI systems;
- algorithmic transparency;
- conformity assessment procedures;
- post-market monitoring;
- human oversight mechanisms; and
- accountability throughout the AI lifecycle.

Such reforms would establish a predictable regulatory environment capable of supporting innovation while safeguarding fundamental rights.

Establishment of Regulatory Sandboxes

The Government should introduce regulatory sandboxes enabling the controlled testing of innovative AI systems and digital technologies under regulatory supervision. [[FN40]]

Such environments would provide innovators with greater legal certainty while allowing regulators to assess emerging technologies before their large-scale deployment. Regulatory sandboxes have become an increasingly important instrument of innovation governance across the European Union and should form part of North Macedonia's long-term digital policy strategy.

Promotion of Open Licensing and Open Data

Finally, national policy should actively promote the wider use of **open licensing models** and **open data**, particularly within publicly funded scientific research, higher education, and public administration.

Expanding access to publicly available digital resources would encourage innovation, improve transparency, strengthen research collaboration, and support evidence-based policymaking, while remaining fully consistent with European standards governing intellectual property and personal data protection.

Interim Conclusion

The proposed recommendations provide a structured roadmap for the gradual modernisation of North Macedonia's digital regulatory framework. Their implementation would contribute to greater legislative coherence, stronger institutional capacity, enhanced legal certainty, and closer alignment with the European Union's evolving digital governance architecture.

Taken together, these measures would support the responsible development of artificial intelligence, strengthen intellectual property protection, facilitate digital innovation, and promote a resilient, secure, and competitive digital economy.

38Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act), OJ L, 12 July 2024.

39Regulation (EU) 2024/1689 (Artificial Intelligence Act), including Arts. 9–15 on requirements for high-risk AI systems and Arts. 57–63 on regulatory sandboxes and innovation support.

6. Conclusion

This policy paper has examined the extent to which North Macedonia's legal framework governing digital transformation aligns with the European Union's evolving regulatory architecture for artificial intelligence, intellectual property, digital services, cybersecurity, and personal data protection.

The analysis demonstrates that North Macedonia has established a relatively comprehensive legislative foundation in these areas through the gradual harmonisation of national legislation with the *acquis communautaire*. Nevertheless, significant regulatory and institutional challenges continue to impede the effective implementation of this legal framework.

The principal weaknesses identified do not arise from the absence of legislation but rather from regulatory fragmentation, insufficient horizontal coordination among legal regimes, limited integration of artificial intelligence into existing legislation, and inadequate institutional capacities for implementation and enforcement. These structural deficiencies create legal uncertainty, hinder innovation, and reduce the effectiveness of digital governance.

The analysis further highlights several priority areas requiring legislative reform, including the regulation of AI-generated content, Text and Data Mining (TDM), digital platform governance, algorithmic transparency, software-related inventions, digital industrial designs, and the practical implementation of data protection principles such as *privacy by design* and *privacy by default*. In parallel, stronger institutional coordination, improved supervisory capacities, and greater interoperability between competent authorities are essential prerequisites for the successful implementation of future reforms.

The proposed policy recommendations provide a structured roadmap for strengthening North Macedonia's digital regulatory framework during the period 2026–2028. Their implementation would contribute to greater legal coherence, improved institutional effectiveness, enhanced protection of intellectual property rights, and the responsible development of artificial intelligence in accordance with European values and regulatory standards.

From a broader policy perspective, digital transformation should not be regarded solely as a technological process but rather as a comprehensive legal, institutional, and governance challenge. Effective regulation requires an integrated approach that combines technological innovation with robust legal safeguards, institutional accountability, respect for fundamental rights, and sound public policy.

As North Macedonia continues its European integration process, the progressive alignment of its digital regulatory framework with the European Union acquis will play an increasingly important role in strengthening the rule of law, enhancing economic competitiveness, fostering innovation, and promoting sustainable digital development. Future reforms should therefore focus not only on legislative harmonisation but also on building resilient institutions capable of implementing and enforcing complex digital regulations within an increasingly AI-driven society.

Ultimately, the successful governance of digital transformation will depend upon the state's ability to establish a coherent, transparent, and future-oriented regulatory framework that simultaneously encourages innovation, protects fundamental rights, and ensures legal certainty for citizens, businesses, researchers, and public institutions. Achieving this balance will be essential for supporting North Macedonia's transition towards a resilient digital economy and its successful integration into the European Digital Single Market.

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DEVELOPMENT OF AUDIT INSTRUMENTS BASED ON STUDENT EXPECTATIONS AND INDUSTRY RELEVANCE IN THE DIGITAL ERA

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ABSTRACT
This study aims to reconstruct the internal quality audit instrument in higher education by harmonizing the expectations of prospective students (Generation Z) with institutional standards. The background of this research is the widening gap between conventional audit standards—which focus on administrative compliance—and the pragmatic needs of students regarding industry relevance. Using a mixed-method approach, this study analyzes survey data from 507 respondents regarding interests in new study programs (Entrepreneurship, Digital Business, IT, Digital PR, and DKV). The findings reveal a significant gap: 61.3% of respondents prioritize the availability of business mentors over academic degrees, and 60.5% prefer project-based learning over theory. Based on this Gap Analysis, this study proposes a Feed-Forward Career Validation Mechanism and a New Audit Instrument Matrix that converts student preferences into measurable quality indicators. The conclusion suggests that Higher Education Quality Assurance must shift from Compliance-Based to Relevance-Based to ensure graduates' employability in the digital era.
Keywords: Quality Assurance; Gap Analysis; Student Expectation; Feed-Forward Audit; Higher Education Management

A STRATEGY FOR TRANSFORMING GRADUATE QUALITY AUDITS THROUGH THE INTEGRATION OF CAREER PATH READINESS INDICATORS INTO HIGHER EDUCATION QUALITY ASSURANCE

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ABSTRACT

The misalignment between graduate competencies and digital industry needs demands a redefinition of quality assurance systems in higher education. This article examines the development of graduate quality audit ideas by integrating Career Path Readiness (CPR) indicators into the Setting, Implementation, Evaluation, Control, and Improvement (PPEPP) cycle. Using a conceptual-analytical approach, this research identifies that conventional administrative quality audits need to shift toward predictive outcome-based audits. The analysis results show that the dimensions of career self-efficacy, career planning, and digital adaptability are crucial parameters that must be measured during the study period, not just after graduation. The integration of Career Registration Methodology (CRM) into internal quality audit instruments is proven to provide accurate longitudinal data for continuous curriculum and career service improvement.

Keywords: Internal Quality Audit; Career Path Readiness; Quality Assurance; Digital Higher Education; PPEPP.

A COMPARATIVE ANALYSIS OF AMI RESULTS IN RELATION TO THE PROSPECTS FOR ACHIEVING 'EXCELLENT' ACCREDITATION AT LAMEMBA

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ABSTRACT
This study analyzes the comparative transformation of Internal Quality Audit (AMI) results between Cycle 17 (Academic Year 2024/2025) and Cycle 18 (Academic Year 2025/2026) at the Bachelor of Management Study Program, Faculty of Economics and Business, Universitas 17 Agustus 1945 Samarinda. Furthermore, it evaluates the study program's potential to achieve "Unggul" (Superior) accreditation status under the standards set by the Independent Accreditation Provision for Economics, Management, Business, and Accounting (LAMEMBA). Using a qualitative comparative research design based on institutional quality document reviews and the PPEPP (Planning, Implementation, Evaluation, Control, Improvement) quality control cycle, the findings reveal a significant paradigm shift. In Cycle 17, the study program accumulated 138 non-conformity findings, consisting of 6 Major KTS, 83 Minor KTS, and 49 Observations, primarily driven by incomplete administrative supporting evidence, low lecturer participation records in research/community service, and fragmented academic information systems. In Cycle 18, following systematic corrective actions, non-conformities were reduced to 0 Major KTS and 0 Minor KTS, achieving a 93.94% compliance rate across 62 indicators with only 4 minor Observations remaining. These observations pertain to target volume optimization, including Intellectual Property Rights (HKI) quantity, active Implementation Agreements (IA), and scholarship coverage. The analysis confirms that the S1 Management Study Program has established a mature internal quality assurance system (SPMI) and possesses a strong probability of attaining "Unggul" accreditation, provided the remaining quantitative targets are fully realized prior to the LAMEMBA SelfEvaluation Report submission.
Keywords: Internal Quality Audit; LAMEMBA Accreditation; Quality Assurance System; Superior Accreditation; Management Study Program

ANALISIS STRATEGI PENGEMBANGAN PERGURUAN TINGGI SWASTA DI SAMARINDA DALAM MENGHADAPI PEMINDAHAN IBU KOTA NUSANTARA

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ABSTRACT
This research aims to analyze the strategic position of Private Higher Education Institutions (PTS) in Samarinda using a qualitative SWOT matrix. Amidst the relocation of the National Capital City (IKN) to East Kalimantan, PTS face significant challenges and opportunities. Data was gathered through qualitative observations and literature reviews regarding the regional educational landscape. The findings indicate that while PTS possess high flexibility and strong local community ties, they are hindered by limited research capacity and high tuition dependency. The study concludes that PTS must leverage IKN momentum by developing specific vocational programs and strengthening industry partnerships to remain competitive against expanding State Universities (PTN). Furthermore, the research highlights the critical role of OIKN in bridging the gap between national targets and local institutional readiness.
Keywords: Private Higher Education; SWOT Analysis; Samarinda; IKN; Strategic Management

GAP ANALYSIS AND RECOMMENDATIONS FOR IMPROVING THE QUALITY OF HIGHER EDUCATION

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ABSTRACT

The Internal Quality Audit (AMI) at the Law Study Program, Faculty of Law, Universitas 17 Agustus 1945 Samarinda, revealed several key findings in the areas of education, research, and community service (PkM) for the academic year 2023/2024. In the education standards, the study program has formulated graduate competency standards but these have not yet been legalized or disseminated. The existing curriculum is from 2014 and consists only of a list of courses and Semester Learning Plans (RPS), rather than a comprehensive curriculum document. Lecture planning has been carried out, but without official meeting minutes and comprehensive monitoring and evaluation. Regarding learning facilities and infrastructure, implementation is not optimal, lacking clear Annual Work and Budget Plans (RKAT) and monitoring evaluation involving the Faculty Quality Assurance Unit (UPMF). Furthermore, the study program has not developed academic guidelines and lacks clear learning assessment standards. Strong leadership, formal policies and procedures, and consistent strategic planning are also identified as weaknesses.

In the research standards, it was found that the research roadmap has not been updated according to current developments, not all lecturers are actively involved in research, and there is a lack of motivation or support for lecturers to participate. Adequate documentation of the research roadmap, systematic planning, incentives, and effective monitoring-evaluation mechanisms remain areas for improvement. For community service (PkM) standards, the absence of a clear and structured PkM roadmap, along with the lack of formal guidelines for implementing and reporting PkM activities, has resulted in suboptimal activity execution and insufficient documentation of contributions and performance evaluation. Overall, the condition of the Law Study Program, Faculty of Law, is already very good, but improvements are needed in the identified areas to ensure proper program documentation. The main recommendation from the AMI is to enhance document archiving for both hard and soft files. Follow-up actions from the AMI results should include continuous improvement, monitoring, and evaluation.

Keywords: IInternal Quality Audit; Education; Community Service; Curriculum; Roadmap;

QUALITY ASSURANCE IN HIGHER EDUCATION BASED ON THE P.D.C.A CYCLE

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ABSTRACT
This study analyzes the learning assurance system in Law Program University XYZ, focusing on the trend of student admissions and active enrollment from the Academic Year 2022/2023 to 2025/2026. The empirical data reveals a downward trend in student selection numbers and a high rate of non-active students. To resolve these challenges, this article proposes a learning assurance framework using the Plan-Do-Check-Act (PDCA) quality cycle. Additionally, a quantitative simulation of the worst-case scenario is formulated to project the potential financial and academic risks if corrective actions are neglected. The simulation shows that failure to mitigate these issues could lead to an institutional cash flow loss and a potential downgrade in BAN PT accreditation due to skewed student-to-faculty ratios. Tactic follow-up recommendations include financial relaxations, Early Warning Systems integration via SIAKAD, and outcome-based curriculum realignment.
Keywords: Learning Assurance; PDCA Cycle; Student Retention; Worst-case Simulation.

DIGITAL BEHAVIOUR AND ONLINE VERBAL AGGRESSION: EDUCATIONAL PERSPECTIVES FOR SAFER ONLINE COMMUNITIES

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Abstract
Social media and digital communication have revolutionized how people interact, voice their opinions, and engage in online communities. These platforms have given people more opportunities for communication and civic engagement, but have also been a breeding ground for online verbal aggression, such as abusive language, trolling, hate speech, harassment, and cyberbullying. Around the world, about 32% of pupils are bullied by other pupils and up to one in ten children are cyberbullied, according to UNESCO. In addition, a UNICEF U-Report survey of 30 countries revealed that one in three youth had been bullied online, and one in five had missed school due to cyberbullying and online violence. The results show that aggressive online behaviour is not just a digital problem, but a growing issue in education and society. This conceptual paper explores the phenomenon of online verbal aggression from the perspective of education and digital behaviour. The study employs a narrative review of the literature to synthesize the research on digital citizenship, cyberbullying, media and information literacy, social-emotional learning, and online disinhibition. It examines the role of anonymity, algorithmic engagement, group identity and the normalization of hostile online interactions in verbal aggression through digital platforms. The paper also explores the educational implications of such conduct, such as lower empathy, psychological stress, and lower levels of interpersonal relationships, and lower quality of online participation among youth.The paper suggests that the educational system has a pivotal place in combating verbal aggression online through embedding digital citizenship, ethical online communication, media literacy and social-emotional learning in the curriculum. Prevention is a more effective way to address education, and should involve teaching empathy, critical thinking, respectful communication and responsible digital engagement, rather than just discipline. The study concludes that there is a need for a coordinated approach between educators, families, policy makers and technology platforms to address online verbal aggression. Education is vital to a future of digital ethics, fostering inclusive, respectful, and safe online spaces in a highly connected world.
Key Words: Online Verbal Aggression, Digital Behaviour, Digital Citizenship, Cyberbullying, Media Literacy.

PSYCHOLOGICAL AND PEDAGOGICAL FEATURES OF THE EFFECTIVENESS OF DISTANCE LEARNING

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Abstract

According to the Ministry of Education and Science of Ukraine, at the beginning of the 2026/2027 academic year in our country, 1,306 schools operate remotely (approximately 10.9% of the total number), students study in a blended format (combining in-person classes and online lessons) in 2,211 schools (18.5%), and 8,424 general secondary education institutions work in-person (nearly 70.6%). However, the latter must also be ready at any time to switch from offline to online learning due to massive bombardments and the state of martial law in the country.

The effectiveness of distance learning for schoolchildren is determined not only by the technical capabilities of the educational environment, but also by the psychological and pedagogical conditions of organizing learning activities. Therefore, one of the main tasks of effective distance learning is not merely the transmission of knowledge, but the formation of each student's ability to learn independently, search for information, and apply it in practice. In other words, pupils must acquire self-directed learning skills, as this very ability can mitigate learning loss during distance education. It is also crucial that every student has the opportunity to independently plan their activities, perceive progress in mastering the material, and be actively engaged in educational interaction.

Thus, the psychological effectiveness of distance learning directly depends on the extent to which the educational environment provides the student with autonomy, a sense of personal efficacy, and the opportunity to maintain learning interaction. It is from these positions that one can explain why motivation in a distance learning environment can both increase and decrease. Excessive control, rigid scheduling, and overload with synchronous interaction restrict the learner's autonomy and, accordingly, reduce their intrinsic motivation. Conversely, a flexible organization of the educational process, the ability to work at one's own pace, and the freedom to choose the time for completing assignments contribute to its preservation and development.

In this context, asynchronous learning acquires particular importance. It allows the student to organize their activity according to individual capabilities, which directly supports the need for autonomy. Furthermore, working with materials at a convenient time reduces the psychological burden associated with the need for a constant online presence and creates more comfortable conditions for acquiring knowledge. Thus, the asynchronous format not only increases learning flexibility, but also positively affects the motivational component of the educational process.

Keywords: distance learning, educational effectiveness, learner autonomy, asynchronous learning, learning motivation.

ITEM ANALYSIS AS A MEANS OF IMPROVING THE QUALITY OF MULTIPLE-CHOICE QUESTIONS

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Abstract
Educational assessment plays a central role in teaching and learning because it provides evidence about whether educational objectives have been achieved. Multiple-choice questions (MCQs) are widely used because they permit broad content coverage and objective scoring. Nevertheless, the usefulness of an MCQ test depends largely on the quality of the individual items that make up the test. This paper reviews item analysis as a practical approach for improving the quality of multiple-choice questions. Particular attention is given to item difficulty, item discrimination, and distractor analysis. Item difficulty shows the proportion of examinees who answer an item correctly and provides evidence about the relative ease or difficulty of an item for a particular group. Item discrimination indicates how effectively an item differentiates between examinees who perform relatively well and those who perform relatively poorly on the test. Distractor analysis examines whether incorrect alternatives are plausible and are functioning as intended. The paper also discusses how problematic items can reduce the usefulness of test scores and create unnecessary confusion for examinees. The review concludes that item analysis should be an important part of test development and review because it provides evidence that can guide the retention, revision, or removal of individual items. When combined with careful item writing and expert review, item analysis can contribute to stronger, more reliable, valid, and useful multiple-choice assessments.
Keywords: Item analysis; multiple-choice questions; item difficulty; item discrimination; distractor analysis; educational assessment; test quality.

Introduction
Educational assessment is an integral part of the teaching and learning process. It provides information that can be used to determine the extent to which educational goals have been achieved and supports decisions concerning grades, placement, advancement, instructional needs, curriculum planning, and educational reform. Assessment may take several forms, including tests, observations, interviews, and behavioural monitoring (Kizlik, 2012). A test is one structured method of obtaining evidence about a learner's knowledge, skills, abilities, or mastery of particular content.
In many educational settings, especially formal school examinations, achievement tests remain an important source of evidence about students' learning. In Nigeria, achievement tests continue to occupy a prominent position in educational assessment (Afemikhe & Imobekhai, n.d.). Among the available test formats, multiple-choice questions are particularly useful because they can cover a relatively wide range of content and can be scored objectively. However, the use of MCQs alone does not guarantee a quality assessment. The quality of the test depends greatly on the quality of the items from which it is constructed.
A test item is an individual question, statement, exercise, problem, or task to which an examinee is expected to respond. In an MCQ, the item normally contains a stem and a number of response alternatives, including a keyed correct answer and incorrect alternatives known as distractors. Each item should make a meaningful contribution to the overall test. Consequently, test developers need a systematic way of determining whether individual items are functioning as intended. Item analysis provides this opportunity. It involves examining examinees' responses to individual items and using the resulting information to judge item quality. The process can reveal items that are too easy,

too difficult, poorly discriminating, or supported by weak distractors. Such information enables test developers to improve an item before it is reused or to remove it when revision is unlikely to solve the problem.

Concept of Item Analysis

Item analysis is the process of collecting, summarising, and using information from examinees' responses to evaluate the quality of individual test items (Shete et al., 2015). It is therefore concerned with the functioning of individual questions rather than only the total test score. The process helps the test developer determine whether an item is making the contribution expected of it. A useful way to understand item analysis is to regard it as a form of quality control. Just as a building is inspected to determine whether its different parts meet required standards, individual test items can be examined to determine whether they function adequately within the assessment. The purpose is to retain items with desirable characteristics, improve items with identifiable weaknesses, and eliminate items that fail to contribute appropriately to the test (Sari, 2017; Quaigrain & Arhin, 2017).

Item analysis can provide information about how examinees respond to particular questions and can help teachers identify items that are especially easy or difficult. It may also provide useful feedback for reviewing aspects of instruction or content coverage. In this sense, item analysis supports the broader goals of improving test reliability and validity (Salkind, 2008). Item analysis should complement, rather than replace, qualitative review. Qualitative review depends on expert judgement and is particularly important during item development, when response data are not yet available. Statistical item analysis is normally conducted after items have been administered and actual response data can be examined. Both approaches have the same broad purpose: identifying problematic items and improving the quality of the assessment.

Item Difficulty Index

The item difficulty index, also referred to as item facility, is the proportion or percentage of examinees who answer an item correctly (Brown, 2004; Ding & Beichner, 2009; Urbina, 2004). Although the term "difficulty" is commonly used, a higher difficulty index indicates that an item is easier for the group being assessed because a larger proportion of examinees answered it correctly. For a dichotomously scored multiple-choice item, the index can be expressed as: Item Difficulty (p) = Number of examinees answering correctly / Total number of examinees For example, if 75 out of 100 examinees answer an item correctly, the item difficulty index is 0.75, or 75%. If only 35 out of 100 answer correctly, the index is 0.35, or 35%. Thus, the index ranges from 0 to 1, or from 0% to 100%. The difficulty index is useful for identifying the relative level of challenge presented by an item. An item that almost everyone answers correctly provides limited information for differentiating examinees. Similarly, an item that almost everyone answers incorrectly may also provide limited information about differences in achievement. However, difficulty should always be interpreted in relation to the purpose of the test and the characteristics of the examinee group. An item that is appropriately difficult for one assessment may not be appropriate for another.

Item Discrimination Index

Item discrimination refers to the ability of an item to differentiate between examinees who perform relatively well on the overall test and those who perform relatively poorly. In a well-functioning assessment, examinees who have demonstrated stronger mastery of the tested material should generally have a higher probability of answering an appropriate item correctly than examinees who have demonstrated weaker mastery. The discrimination index therefore provides information about the extent to which an item is consistent with the overall pattern of performance on the test. An item with desirable discrimination tends to be answered correctly more frequently by higher-performing examinees. An item with poor or negative discrimination requires further investigation because it may be poorly written, ambiguous, incorrectly keyed, excessively difficult, or affected by weak distractors. Discrimination should not be interpreted mechanically. A low value does not automatically mean that an item has no educational value. Instead, it signals that the item deserves closer examination. The wording, answer key, content relevance, level of difficulty, and response alternatives should all be reviewed before a final decision is made. The practical importance of item discrimination is that it helps the test developer identify questions that are contributing to the intended measurement. When an item

successfully distinguishes examinees who have mastered the tested material from those who have not, it is more likely to contribute positively to the overall quality of the test.

Distractor Analysis

Distractors are the incorrect alternatives presented alongside the correct answer in a multiple-choice question. A good distractor should be plausible enough to attract an examinee who does not know the correct answer, while remaining clearly incorrect to an examinee who has mastered the content. Distractor analysis examines how frequently each option is selected and whether the incorrect alternatives are functioning as intended. A distractor that is almost never selected may be a non-functioning distractor. It may be obviously wrong, unrelated to the question, poorly written, or designed in a way that gives away the correct answer. Effective distractors are often based on common misconceptions, likely errors, incorrect assumptions, or reasonable but incorrect interpretations. Their role is not to confuse students unnecessarily, but to provide meaningful alternatives that allow the item to distinguish between examinees with different levels of understanding (Owolabi et al., 2017; Quaigrain & Arhin, 2017). Distractor analysis adds an important dimension to item evaluation because an item can have an acceptable difficulty level while still having poorly functioning alternatives. Examining the selection pattern for each option can therefore help the test developer determine whether the complete MCQ is working as intended.

Item Analysis and Improvement of MCQ Quality

The central value of item analysis lies in the decisions it makes possible. Rather than assuming that all questions contribute equally to an assessment, the test developer can use empirical evidence to determine which items are performing well and which require attention. Item difficulty helps identify questions that are unusually easy or difficult for the group. Item discrimination indicates whether the question differentiates appropriately between stronger and weaker examinees. Distractor analysis reveals whether the incorrect alternatives are sufficiently plausible and whether they attract examinees in a meaningful way. Taken together, these forms of evidence provide a more complete picture of item functioning. Poorly functioning items may arise for several reasons. An item may contain confusing wording, lack a clear correct response, contain more than one potentially correct alternative, or include distractors that are obviously wrong. Supporting diagrams, pictures, graphs, or other stimuli may also be unclear or misleading. In addition, an item may assess content that does not fit the construct or content domain represented by the rest of the test. Such problems matter because the quality of a test is influenced by the quality of its constituent items. Even a small number of problematic items may affect the reliability and validity of test scores and may unnecessarily consume students' time and attention. For this reason, weak items should not simply be reused without review. A practical item-development cycle can therefore involve five broad stages: writing the item, conducting expert review, administering the test, analysing item performance, and revising or removing weak items. Strong items can then be retained in an item bank for future use. This repeated process allows test developers to build a stronger collection of questions over time.

Practical Implications for Teachers and Examination Bodies

Item analysis has direct implications for classroom teachers, examination bodies, educational researchers, and institutions responsible for assessment. Teachers can use item analysis to review classroom tests and identify questions that should be improved before being used again. Examination bodies can use the same evidence to strengthen item banks and improve the quality of formal examinations. Researchers can also use item analysis when developing or evaluating objective instruments for data collection. For examinees, better item quality can contribute to clearer and fairer assessment. Students should be assessed primarily on the knowledge or ability that the test is intended to measure, rather than on their ability to interpret unnecessarily confusing questions. Well-functioning distractors and clearly written stems can reduce avoidable ambiguity and make the assessment experience more meaningful. However, statistical item indices should always be interpreted alongside professional judgement. Content relevance, curriculum objectives, the intended use of scores, and the characteristics of the target population should be considered before an item is retained, revised, or deleted. Item analysis is most effective when statistical evidence and expert judgement are used together.

Conclusion

Item analysis is an important approach to improving the quality of multiple-choice questions. It provides empirical evidence about how individual items function and support informed decisions about whether items should be retained, revised, or removed. The three major components discussed in this paper, item difficulty, item discrimination, and distractor analysis, provide complementary information. Item difficulty indicates the proportion of examinees who answer an item correctly and helps describe its relative ease or difficulty. Item discrimination indicates how effectively an item differentiates between stronger and weaker examinees. Distractor analysis examines whether the incorrect alternatives are plausible and are performing the function for which they were designed. The overall quality of an assessment depends substantially on the quality of the items from which it is constructed. Item analysis should therefore be treated as an integral part of systematic test development rather than as an optional statistical exercise. When combined with careful item writing, expert review, and appropriate interpretation of statistical evidence, item analysis can contribute to more reliable, valid, fair, and useful multiple-choice assessments.

Table 1 Summary of the major components of MCQ item analysis

Component	What it examines	Contribution to test quality
Item difficulty	Proportion of examinees answering correctly	Shows whether an item is relatively easy or difficult
Item discrimination	Difference in item performance between stronger and weaker examinees	Shows whether an item differentiates examinees appropriately
Distractor analysis	Selection and functioning of incorrect alternatives	Identifies plausible and non-functioning distractors

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A STUDY ON THE SDGS POLICY OF INCLUSIVE EDUCATION FOR PEOPLE WITH DISABILITIES IN SAMARINDA CITY

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ABSTRACT
The research raised the formulation of the problem of how to study the SDGs Policy on Inclusive Education for People with Disabilities of Senior High School (SMAN) 8 Samarinda. This research itself is a descriptive qualitative research. The focus of this research includes several aspects, namely teachers, curriculum, infrastructure and the role of parents. From the results of research and discussion, it is concluded that the implementation of inclusive education policies (inclusive schools) at SMAN 8 Samarinda is running well. Every stakeholder, including the government, schools and parents, work well together to support the policies organized at SMAN 8 Samarinda. By bringing all aspects together the school can become a learning environment that supports equality, respects diversity and enables each learner to reach his/her potential optimally. –
Key words: Inclusive Education, Children with Special Needs

ADSORBING & DESTRUCTURING THE TABUN BY C20 FULLERENE

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ABSTRACT

Many researchers began to study about the properties of Tabun in order find some ways to control this agent with less toxic products. It seems the use of sorbents could be a way to make it inactive, without such dangerous side effects. Tabun, toxic chemical substance, a colorless and tasteless species with a faint fruity odor, is classified as a strong nerve agent because this compound extremely interferes with normal functioning of the nervous system. The low pressure gases form of Tabun would have a brown color, but in high pressure the gas seems to be clear and colorless. The manufacturing process of Tabun consisted of two separated steps.

Some reports, have examined the possibility of adsorption of Tabun or other chemical agents by using nano-sized particles like nanotubes. Moreover, some of the recently published papers reveal about the ability of fullerenes especially C20 fullerene semiconductor in sensing, adsorbing and reacting with some chemical species like dienes, dipoles, aromatics, and hazardous air pollutants. Due to these facts and also due to the last recent reports that revealed about the unique properties of fullerenes species C20 nano-sized carbon cage; in this project, we have tried to investigate the possibility of C20 fullerene both in adsorption, and in detection of Tabun nerve agent. The results showed in all of the considered cases containing, N-doped, B-doped and also the C20 fullerene, the adsorption proceeds via stepwise pathways.

Keywords: Tabun, Adsorbing, C20, dope, toxic.

CHROMIUM(VI) REMOVAL FROM WATER SOLUTIONS USING POLYVINYL CHLORIDE BASED ELECTROSPUN NANOFIBER DISK CONTAINING A DEEP EUTECTIC SOLVENT

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ABSTRACT
The separation, recovery, and removal of Cr(VI) from the water and wastewater samples are important, because it is among the most toxic chemical species with high toxicity and very useful in different industries. Electrospun nanofibers bear some advantages including ease of production, low cost, high porosity, low weight, and high surface to volume ratio. These advantages make them as potential candidates in separation aims. Application of electrospun nanofibers results in limiting the use of organic solvents, which are typically expensive and flammable, is limited. The possibility to use the diverse extractants with a base polymer, extend the abilities of electrospun nanofiber-based separations. Deep eutectic solvents (DESs) are biodegradable with low toxicity risks [5]. DESs are formed by the complexation between a hydrogen bond acceptor and a hydrogen bond donor. The specific nature of their constituents has led to their use in diverse fields including extraction and separation processes.
A hydrophobic deep eutectic solvent (DES) composed of menthol and trioctylphosphine oxide was synthesized and characterized by spectroscopic methods. The synthesized DES was incorporated into electrospun nanofiber disks (ENFDs). The 3.5 cm diameter round pieces of selected ENFDs were employed for investigations. ENFDs had an average thickness and weight of 0.063±0.004 mm and 0.059±0.005 g, respectively. The optimized ENFDs (60/40 PVC/DES wt%) were evaluated for Cr(VI) removal from aqueous solutions. Under optimized conditions (50 mL solution containing 20 mg L^{-1} Cr(VI) in 0.5 M HCl), ENFDs achieved ~90% Cr(VI) removal within 5 hours. Back-extraction using 50 mL 1.5 M Na_2CO_3 results in efficiencies of ~85% after 4. ENFDs maintained stable extraction/back-extraction performance over five consecutive cycles (82.0±1.1). Chemisorption and pseudo-second-order mode process were approved by investigating the kinetic and isotherm models. In real samples (well water, zinc plant wastewater, chromium electroplating wastewater), relative recoveries ranged from 93–96% for ENFDs.

Keywords: Menthol/trioctylphosphine oxide deep eutectic solvent, Electrospun nanofiber polymer disk, Chromium(VI) removal

APPLICATION OF THE IONIC LIQUID CYPHOS® IL101 EXTRACTANT FOR THE SOLVENT EXTRACTION/SEPARATION OF HEAVY METALS

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ABSTRACT

Extensive research has been conducted on recovering metals from industrial residues. Among the techniques utilized for such purpose, solvent extraction techniques are the most widely employed method. Extractants play a crucial role in solvent extraction. They transfer metal species from the aqueous phase to the organic phase and directly affect both efficiency and selectivity. Ionic liquids are unique materials with low melting points, remaining liquid at room temperature. ILs exhibit negligible vapor pressure. This minimizes atmospheric release and pollution, leading to their categorization as "green solvents". The combination of low environmental impact and functional adaptability positions them as pivotal tools in sustainable chemistry. Ionic liquids are also widely used as extractants in solvent extraction of metals and organic compounds. They intervene in the extraction of chemical species via its role as a solvating agent or as an anion exchanger.

This study aims to demonstrate the potentials of the ionic liquid Cyphos® IL101 in dichloromethane, for the recovery of cadmium, zinc, cobalt and nickel from chloride solutions. The metals are extracted via an anion-exchange mechanism by the formation of the ion-pairs $[R_2^+][MCl_3^-]_2$ (R^+ is the cation of the ionic liquid). The process accompanied with a high selectivity and efficiency for Cd(II) and Zn(II) over Co(II) and Ni(II), which was attributed to the greater stability of their chloro-complexes. Using hydrochloric aHCl as the chloride source yielded higher extraction percentages for Cd(II) and Zn(II) with respect to NaCl. The difference was explained by the hydration energies of H^+ and Na^+. Efficient back-extraction was achieved using sodium hydroxide for cadmium and ammonia for zinc. Different behavior was observed for the temperature dependency of cadmium and zinc ions by the studied extractant. The results demonstrate the potential of these methods for the separation and recovery of metals from industrial residues.

Keywords: Heavy metals, Separation, Solvent extraction, Cyphos® IL101

GENERATIVE ARTIFICIAL INTELLIGENCE IN CHEMISTRY EDUCATION: A BIBLIOMETRIC ANALYSIS OF RESEARCH TRENDS, EMERGING THEMES, AND FUTURE DIRECTIONS

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Abstract
The drastic emergence of Generative Artificial Intelligence (GenAI) has begun to reshape chemistry education by introducing new possibilities for personalised learning, automated feedback, problem-solving, content generation, and interactive explanation of complex chemical concepts.
This study presents a bibliometric analysis of the research literature on generative AI in chemistry education, mapping publication trends, influential authors and institutions, keyword co-occurrence networks, and thematic clusters to characterize the intellectual structure of this emerging field. Using data extracted from major scientific databases (e.g., Scopus), a corpus of relevant publications was analyzed through quantitative bibliometric techniques which includes citation analysis, co-authorship mapping, and keyword co-occurrence analysis is complemented by qualitative interpretation of dominant research themes. Moreover, this analysis will examine publication growth, citation patterns, influential authors, institutions, countries, journals, collaboration networks, co-citation structures, bibliographic coupling, and keyword co-occurrence.
The study will further identify major thematic clusters and emerging research directions concerning AI-supported learning, organic reaction mechanisms, chemical reasoning, problem-solving, assessment, AI literacy, and the reliability of AI-generated chemical content. By mapping the intellectual and conceptual structure of this developing field, the study seeks to identify research gaps and emerging opportunities for future investigation. The findings are expected to provide researchers and chemistry educators with a clearer understanding of how GenAI is evolving within organic chemistry education and to support the development of pedagogically informed and responsible approaches to AI integration in chemistry teaching and learning.
Keywords: Generative Artificial Intelligence; Organic Chemistry Education; Bibliometric Analysis; Chemistry Education; ChatGPT; Artificial Intelligence in Education; AI-Supported Learning; Bibliometrix

SPECTROPHOTOMETRIC DETERMINATION OF CR(VI) AFTER SOLID-PHASE EXTRACTION-PRECONCENTRATION USING IONIC LIQUID-CONTAINING POLYMERIC ELECTROSPUN NANOFIBERS

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ABSTARCT
The serious threat posed by Cr(VI) to human health and the environment has motivated the development of cost-effective, rapid, simple, and sensitive monitoring methods. To improve the detection limit and eliminate potential interferences arising from complex sample matrices, various adsorbents have been developed for solid-phase extraction of Cr(VI). Recently, polymeric electrospun nanofiber disks containing suitable extractants and incorporated into filtration devices have been successfully applied for the preconcentration of metal ions. Their high specific surface area and enhanced stability resulting from entrapment of the extractant within the polymer matrix make them promising alternatives to conventional octadecyl-bonded silica disks for solid-phase extraction and determination of target analytes.
In this study, electrospun nanofiber (ENF) disks were applied as a solid phase for extraction and preconcentration of Cr(VI), and then determination by UV-Vis spectroscopy using diphenylcarbazide as the coloring reagent. The optimized ENF disks were composed of 50 wt% polyvinyl chloride and 50 wt% trihexyltetradecylphosphonium chloride ionic liquid. The electrospinning parameters including applied voltage, injection rate, and needle-to-cpllector distance, were optimized. AFM, FESEM, BET, and stress-strain analyses were employed to characterize the prepared disks. A 4.7-cm-diameter disk was placed in a filtration apparatus, and 250 mL of sample solution containing 1 mg/L Cr(VI) at pH 1.2 was passed through the disk at 0.9 mL/min. The retained Cr(VI) was eluted with 25 mL of 1 M nitric acid at 1 mL/min. The method exhibited a working range of 0.010–10 mg/L, a limit of detection of 0.006 mg/L, and a concentration factor of 40. The developed disk remained stable for at least four consecutive extraction/back-extraction cycles without detectable changes in performance. Intra- and inter-day relative standard deviations for 1 mg/L Cr(VI) were below 3%. The proposed method was successfully applied to the determination of Cr(VI) in synthetic and water samples.

Keywords
Low-level determination of Cr(VI), Preconcentration, Solid-phase extraction, Electrospun nanofibers, Ionique liquids

TUNING THE ELECTRONIC AND OPTICAL PROPERTIES OF RUTHENIUM SENSITIZERS FOR DYE-SENSITIZED SOLAR CELLS

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ABSTRACT

Ruthenium-based sensitizers are promising photoactive materials for dye-sensitized solar cells (DSSCs) because of their favorable electronic and optical properties. In this work, a computational investigation was performed to evaluate how modifications of the auxiliary ligands affect the structural, electronic, optical, and charge-transfer characteristics of ruthenium sensitizers. A reference N3-type complex and two modified derivatives, obtained by replacing sulfur with oxygen (N3–O) or selenium (N3–Se), were examined using density functional theory (DFT) and time-dependent density functional theory (TD-DFT). Geometry optimization, frontier molecular orbital analysis, and simulated absorption spectra were investigated in both the gas phase and acetonitrile solvent. The results reveal that ligand modification significantly influences the electronic structure and optical response of the studied sensitizers. Replacement of sulfur by oxygen produces a blue shift in the absorption spectrum and increases absorption intensity, although with a comparatively narrower spectral coverage. In contrast, selenium incorporation induces a red shift and extends the absorption response toward the near-infrared region. The selenium-containing derivative also exhibits enhanced intramolecular charge-transfer characteristics, indicating a favorable combination of broad light absorption and efficient electron-transfer capability. The oxygen-containing derivative, on the other hand, shows improved absorption intensity. Overall, the results demonstrate that modification of the coordinating atoms in ruthenium-based sensitizers provides an effective strategy for tuning their electronic levels, absorption behavior, and charge-transfer properties. These findings provide useful theoretical insights for the rational design and optimization of ruthenium sensitizers with improved photovoltaic characteristics for next-generation DSSCs.

Keywords: Dye-sensitized solar cells; Ruthenium-based sensitizers; Density functional theory; TD-DFT; Electronic properties; Absorption spectra; Intramolecular charge transfer.

FLAVONOID-MEDIATED SUPPRESSION OF LYMPHOCYTE RESPONSES IN SPLENOCYTES AND THYMOCYTES

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Abstract
The search for plant-derived bioactive compounds capable of modulating immune responses has gained increasing attention, particularly in the context of inflammatory and immune-related disorders. *Smyrnium olusatrum* L. (Apiaceae) is a traditionally used Mediterranean medicinal plant whose biological activities remain insufficiently explored. The present study investigated the immunomodulatory potential of a flavonoid-rich fraction obtained from the seeds of *S. olusatrum*, with particular emphasis on its effects on splenocyte and thymocyte responses.
The flavonoid-rich fraction was evaluated in Concanavalin A (Con A)-stimulated splenocytes and thymocytes to assess its capacity to modulate lymphocyte responses. Cell viability was simultaneously examined using Trypan blue exclusion and neutral red assays to distinguish immunoinhibitory activity from nonspecific cytotoxic effects. The flavonoid fraction was tested at concentrations ranging from 1 to 30 µg/mL.
The flavonoid fraction produced a concentration-dependent inhibition of Con A-induced splenocyte and thymocyte responses. Significant immunoinhibitory effects were observed across the tested concentration range, indicating a pronounced capacity of *S. olusatrum* flavonoids to modulate lymphocyte activation. However, the inhibitory response was accompanied by alterations in cell viability at higher concentrations, suggesting that both direct modulation of lymphocyte responses and cytotoxic effects may contribute to the observed activity.
Taken together, these findings provide evidence that the flavonoid-rich fraction of *S. olusatrum* seeds possesses marked immunoinhibitory activity in primary splenocyte and thymocyte models. The observed concentration-dependent response highlights the immunomodulatory potential of *S. olusatrum* flavonoids while emphasizing the importance of defining the relationship between immune-cell inhibition and cytotoxicity.
Keywords: *Smyrnium olusatrum* L.; flavonoids; immunomodulation; immunoinhibition; splenocytes; thymocytes; lymphocyte responses.

PRELIMINARY PHYTOCHEMICAL SCREENING OF METHANOLIC EXTRACT OF FRESH FLOWERS OF BARLERIA CRISTATA

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ABSTRACT

This current study has been conducted in order to conduct a preliminary phytochemical analysis of the fresh flowers of *Barleria cristata* through its methanolic extract. Fresh flowers have been collected, extracted with methanol, and then analyzed qualitatively for the presence of phytoconstituents using standard procedures of chemical analysis. The analysis showed the presence of phenolic compounds, flavonoids, carbohydrates, and reducing sugars in the methanolic extract of the flowers. But no presence of alkaloids, saponins, quinones, anthraquinones, and cardiac glycosides was observed in the fresh flowers under the conditions of the experiment. Phenolic compounds and flavonoids indicate the possible presence of secondary metabolites that might have some pharmacological activities such as antioxidant properties. Carbohydrates and reducing sugars suggest the presence of primary metabolites in the flowers of the plant. Hence, it can be concluded that there are some bioactive components in the fresh flowers of *Barleria cristata* which can act as good sources of natural phytoconstituents..
Keywords: *Barleria cristata*, phytoconstituents, fresh flowers, methanol, bioactive

STUDY AND OPTIMIZATION OF LEACHING OF CR(VI)-CONTAMINATED SOILS WITHOUT POTENTIAL INTERFERENCE FROM CR(III) OXIDATION

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ABSTRACT

Some industrial facilities use Cr(VI) compounds in their production processes. Consequently, the presence of this environmental contaminant in the effluents discharged from, or wastes generated by, these facilities is highly likely. Improper management of such effluents and wastes may result in the contamination of water and soil in the vicinity of such industries. Accordingly, monitoring of water and soil around industrial facilities is important for environmental regulatory authorities. Such monitoring, particularly in the case of soils, involves specific complexities and requires careful consideration. The sampling procedures should therefore be designed and implemented in a manner that allows accurate determination of the chromium contaminant concentration while preventing the conversion and oxidation of Cr(III) to Cr(VI).

To meet these requirements, four reagents *i.e.* nitric acid, a sodium hydroxide/sodium carbonate mixture, sodium phosphate, and ethylenediaminetetraacetic acid (EDTA)—were selected for the leaching of Cr(VI) from soil samples, and the resulting extraction efficiencies were evaluated and compared. The effects of the major factors influencing the leaching process, including contact time, volume and concentration of the leaching solution, temperature, and the possibility of oxidation of Cr(III) to Cr(VI), were investigated. Cr(VI) was determined using two methods: spectrophotometry with diphenylcarbazide as the color-developing reagent and flame atomic absorption spectrometry. Leaching experiments were conducted at 25 ± 1 °C using 2.0-g soil samples containing 2–46 mg Cr kg^{-1} soil and 50 mL of each of the following leaching solutions: nitric acid (0.01 M), sodium hydroxide (0.125 M)/sodium carbonate (0.07 M) mixture, sodium phosphate (0.03 M), and EDTA (0.001 M). The results demonstrated that, under the optimized leaching conditions and with the reagents investigated, no conversion of Cr(III) to Cr(VI) occurred. Considering the advantages of using EDTA solution for the leaching of Cr(VI) from soil, EDTA was identified as a suitable leaching reagent for this process.

Keywords

Leaching, Contaminated soils, Cr(VI), Cr(III) oxidation, Ethylenediaminetetraacetic acid

FARKLI COĞRAFİ KÖKENLERDEN BAL ÖRNEKLERİNİN FİZİKOKİMYASAL ÖZELLİKLERİNİN KARŞILAŞTIRMALI DEĞERLENDİRİLMESİ

COMPARATIVE EVALUATION OF THE PHYSICOCHEMICAL PROPERTIES OF HONEY SAMPLES FROM DIFFERENT GEOGRAPHICAL ORIGINS

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ÖZET
Bal, başlıca karbonhidratlardan oluşan ve bunun yanı sıra amino asitler, organik asitler, enzimler, fenolik bileşikler, mineraller ve çeşitli biyoaktif bileşenler içeren doğal bir üründür. Balın fizikokimyasal özellikleri botanik ve coğrafi köken, rakım, iklim, bitki örtüsü, hasat zamanı, olgunlaşma, işleme ve depolama koşullarına bağlı olarak değişkenlik gösterebilmektedir. Özellikle farklı rakım ve mikroklimatik koşullara sahip bölgelerde üretilen ballar arasında kalite özellikleri bakımından farklılıklar ortaya çıkabilmektedir. Bu nedenle, temel fizikokimyasal parametrelerin belirlenmesi, bal kalitesinin değerlendirilmesi ve bölgesel farklılıkların ortaya konulması açısından önem taşımaktadır. Nem içeriği, elektriksel iletkenlik, diastaz aktivitesi, hidroksimetilfurfural (HMF), şeker kompozisyonu, serbest asitlik ve prolin içeriği bu amaçla yaygın olarak kullanılan kalite göstergeleri arasında yer almaktadır. Bu çalışmada, Artvin ili içerisinde farklı coğrafi koşulları temsil eden Ardanuç-Zekeriyaköy Aksu Yaylası, Yusufeli-Erenköy, Şavşat-Ciritdüzü, Murgul-Erenköy ve Borçka-Maçahel Efeler bölgelerinden elde edilen bal örneklerinin fizikokimyasal özellikleri belirlenmiştir. Elde edilen sonuçlar, Artvin'e yakın konumda bulunan üretim bölgeleri arasından seçilen Ağrı-Eleşkirt, Kars-Kağızman, Ardahan-Posof ve Rize-Hemşin'den temin edilen bal örnekleriyle karşılaştırılmıştır. Nem içeriği, elektriksel iletkenlik, prolin içeriği, diastaz aktivitesi, HMF içeriği, şeker kompozisyonu ve serbest asitlik standart analitik yöntemler kullanılarak belirlenmiştir. Böylece hem Artvin ili içerisindeki lokasyonlar arasındaki değişkenlik hem de Artvin ile çevre bölgeler arasındaki benzerlik ve farklılıklar değerlendirilmiştir. Artvin bal örneklerinde prolin içeriği 557–1020 mg/kg, diastaz aktivitesi 16,93–35,97 Gothe, HMF içeriği 1,48–9,31 mg/kg, nem içeriği %15,15–19,50, elektriksel iletkenlik 0,537–1,383 mS/cm ve serbest asitlik 32,22–43,21 meq/kg aralığında belirlenmiştir. Karşılaştırma yapılan bölgelerde ise prolin içeriği 495–565,33 mg/kg, diastaz aktivitesi 13,90–25,34 Gothe, HMF içeriği 0,33–1,14 mg/kg, nem içeriği %16,67–17,77, elektriksel iletkenlik 0,193–1,089 mS/cm ve serbest asitlik 14,93–25,67 meq/kg aralığında bulunmuştur. Tüm örneklerde fruktoz ve glukoz toplamının yüksek, sakaroz düzeylerinin ise düşük olduğu belirlenmiştir. Tüm örnekler Türk Gıda Kodeksi sınırları içinde kalmakla birlikte, Artvin ve karşılaştırma bölgeleri arasında özellikle prolin içeriği ve serbest asitlik bakımından farklılık belirlenmiştir. Bu bulgular, balın fizikokimyasal özelliklerinin üretim bölgesine bağlı olarak değişebildiğini ve yerel ekolojik koşulların coğrafi olarak birbirine yakın bölgelerde dahi bal kalitesi üzerinde etkili olabileceğine işaret etmektedir. Çalışmadan elde edilen sonuçlar, Artvin ballarının bölgesel özelliklerinin ortaya konulmasına katkı sağlamakta ve bu balların kalite özelliklerinin karşılaştırmalı olarak değerlendirilmesi için bir temel oluşturmaktadır.
Anahtar kelimeler: Bal Kalitesi, Fizikokimyasal Özellikler, Coğrafi Köken, Artvin.

ABSTRACT
Honey is a natural product composed primarily of carbohydrates, together with amino acids, organic acids, enzymes, phenolic compounds, minerals, and various bioactive constituents. The physicochemical properties of honey may vary depending on botanical and geographical origin, altitude, climate, vegetation, harvesting time, maturation, processing, and storage conditions. In particular, marked variations in quality characteristics may occur among honeys produced in regions with different altitudes and microclimatic conditions. Therefore, the determination of key physicochemical parameters is important for assessing honey quality and elucidating regional differences. Moisture content, electrical conductivity, diastase activity, hydroxymethylfurfural (HMF), sugar composition, free acidity, and proline content are among the quality indicators widely used for this purpose. In the present study, the physicochemical characteristics of honey samples obtained from Ardanuç-Zekeriyaköy Aksu Yaylası, Yusufeli-Erenköy, Şavşat-Ciritdüzü, Murgul-Erenköy, and Borçka-Maçahel Efeler, representing different geographical conditions within Artvin Province, were determined. The results were compared with samples collected from Ağrı-Eleşkirt, Kars-Kağızman, Ardahan-Posof, and Rize-Hemşin, which were selected as production regions located near Artvin. Moisture content, electrical conductivity, proline content, diastase activity, HMF content, sugar composition, and free acidity were determined using standard analytical methods. Thus, both the variability among locations within Artvin and the similarities and differences between Artvin and the surrounding regions were evaluated. In the Artvin samples, proline content ranged from 557 to 1020 mg/kg, diastase activity from 16.93 to 35.97 Gothe units, HMF content from 1.48 to 9.31 mg/kg, moisture content from 15.15 to 19.50%, electrical conductivity from 0.537 to 1.383 mS/cm, and free acidity from 32.22 to 43.21 meq/kg. In the comparison regions, proline content ranged from 495 to 565.33 mg/kg, diastase activity from 13.90 to 25.34 Gothe units, HMF content from 0.33 to 1.14 mg/kg, moisture content from 16.67 to 17.77%, electrical conductivity from 0.193 to 1.089 mS/cm, and free acidity from 14.93 to 25.67 meq/kg. The combined fructose and glucose content was found to be high in all samples, whereas sucrose levels were low. While all samples complied with the limits of the Turkish Food Codex, differences between Artvin and the comparison regions were observed particularly in proline content and free acidity. These findings suggest that the physicochemical characteristics of honey may vary according to the production region and that local ecological conditions can influence honey quality even across geographically proximate areas. The results of this study contribute to elucidating the regional characteristics of Artvin honeys and provide a basis for the comparative evaluation of their quality attributes.
Keywords: Honey quality, Physicochemical properties, Geographical origin, Artvin.

GİRİŞ

Bal, bal arılarının başta çiçek nektarları olmak üzere bitkilerin canlı kısımlarından veya bitki üzerinde yaşayan bazı böceklerin salgılarından topladıkları doğal maddeleri kendilerine özgü enzimlerle işleyerek, su içeriğini azaltıp petek gözlerinde olgunlaştırmaları sonucunda oluşan kompleks bir doğal üründür (Codex Alimentarius Commission, 2001; Türk Gıda Kodeksi, 2020). İnsan beslenmesinde çok eski dönemlerden beri yer alan bal, yüksek oranda karbonhidrat içermesinin yanı sıra amino asitler, organik asitler, enzimler, mineraller, vitaminler, fenolik bileşikler ve çeşitli uçucu ve biyoaktif bileşenler içermektedir (Bogdanov et al., 2008; Eteraf-Oskouei & Najafi, 2013). Balın temel bileşenlerini fruktoz ve glukoz başta olmak üzere şekerler oluştururken, daha düşük miktarlarda bulunan organik asitler, proteinler, enzimler, mineraller, vitaminler ve fenolik bileşikler de balın besinsel değeri, duyusal özellikleri, stabilitesi ve genel kalite niteliklerinin belirlenmesinde önemli rol oynamaktadır (Bogdanov et al., 2008; Eteraf-Oskouei & Najafi, 2013). Balın kimyasal bileşimi sabit olmayıp üretildiği bölgenin botanik ve coğrafi özelliklerine bağlı olarak önemli ölçüde değişebilmektedir (Rivera-Mondragón et al., 2023; Kiran & Riyaz, 2026). Balın bileşimini doğrudan veya dolaylı olarak etkileyen başlıca çevresel ve botanik faktörler arasında arıların yararlandığı nektar ve salgı kaynakları ile bölgenin bitki çeşitliliği, yükseltisi, sıcaklık değişimleri, yağış rejimi ve mikroklimatik koşulları yer almaktadır (Kiran & Riyaz, 2026). Bununla birlikte, balın özellikleri yalnızca çevresel ve botanik faktörlere bağlı olmayıp balın petekte olgunlaşma süresi, hasat zamanı, arıcılık uygulamaları, işleme koşulları, uygulanan sıcaklık ve depolama süresinden de etkilenebilmektedir (Tosi et al., 2008; Kiran & Riyaz, 2026). Bu etkenlere bağlı olarak balın fizikokimyasal özellikleri üretim bölgeleri arasında değişkenlik gösterebilmektedir. Hatta coğrafi olarak birbirine yakın alanlarda bile yükselti, topoğrafya, bitki örtüsü ve mikroklimatik koşullardaki farklılıklar balın kimyasal bileşimine yansıyabilmektedir (Demir Kanbur et al., 2021). Bu

nedenle kalite değerlendirmelerinin, genel standartlara uygunluğun yanı sıra üretim bölgesinin özgün koşullarını da kapsaması gerekmektedir. Balın kalitesi, olgunluğu, tazeliği ve botanik kökeni çeşitli fizikokimyasal parametreler aracılığıyla değerlendirilmektedir. Nem içeriği, elektriksel iletkenlik, serbest asitlik, prolin miktarı, diastaz aktivitesi, hidroksimetilfurfural (HMF) düzeyi ve şeker kompozisyonu bu amaçla yaygın şekilde kullanılan temel kalite göstergeleridir (International Honey Commission, 2009; Codex Alimentarius Commission, 2001). Fizikokimyasal parametrelerin her biri balın farklı bir özelliğini yansıtır ve tek bir parametreye dayalı değerlendirme balın genel kalite profilini açıklamak için yeterli değildir (Bogdanov et al., 2004; Cilavdaroğlu, 2026). Bu nedenle söz konusu parametrelerin birlikte değerlendirilmesi gerekmektedir. Balın nem içeriği, ürünün olgunluğu ve depolama stabilitesi açısından önemli bir kalite parametresidir. Petek gözlerinde yeterince olgunlaşmamış balın su içeriği yüksek olabilmekte ve yüksek nem özellikle ozmofilik mayaların gelişimi için elverişli koşullar oluşturarak fermantasyon riskini artırabilmektedir (Kiran & Riyaz, 2026). Nem miktarı ayrıca balın viskozitesi, kristalizasyon eğilimi ve raf ömrü üzerinde de etkili olabilmektedir (Singh & Singh, 2018). Bu nedenle Türk Gıda Kodeksi ve uluslararası düzenlemelerde balın nem içeriğine ilişkin sınır değerler bulunmaktadır (Codex Alimentarius Commission, 2001; Türk Gıda Kodeksi, 2020). Bununla birlikte balın nem içeriği yalnızca üretim ve işleme koşullarına bağlı değildir. Bölgenin atmosferik nemi, yağış rejimi, hasat dönemi ve botanik köken de nem içeriğini etkileyebilmektedir (Rivera-Mondragón et al., 2023; Kiran & Riyaz, 2026). Elektriksel iletkenlik ise balın mineral madde, organik asit ve iyonik bileşen içeriğiyle yakından ilişkili bir özellik olup özellikle botanik kökenin değerlendirilmesinde önemli bir göstergedir (Bogdanov et al., 2004). Çiçek balları ile salgı balları ve kestane balı gibi bazı monofloral bal tipleri arasında elektriksel iletkenlik değerleri farklılık gösterebilmektedir (Codex Alimentarius Commission, 2001; Demir Kanbur et al., 2021; Kiran & Riyaz, 2026). Türk Gıda Kodeksi'nde çiçek balı ve kestane balı gibi farklı bal grupları için elektriksel iletkenlik sınırlarının ayrı olarak belirlenmiş olması, bu parametrenin botanik kökenle ilişkili olduğunu desteklemektedir (Türk Gıda Kodeksi, 2020). Buna bağlı olarak, aynı coğrafi bölgede farklı botanik kaynaklardan elde edilen balların elektriksel iletkenlik değerleri de değişkenlik gösterebilmektedir (Demir Kanbur et al., 2021). Elektriksel iletkenlik, botanik kökenin belirlenmesinde en yararlı rutin fizikokimyasal parametrelerden biri olmakla birlikte, bu amaçla diğer fizikokimyasal parametreler ve polen analiziyle birlikte kullanılmaktadır (Bogdanov et al., 2004). Balın serbest asitliği organik asitler, mineral iyonları ve balın olgunlaşması sırasında gerçekleşen biyokimyasal süreçlerle ilişkilidir. Başta glukonik asit olmak üzere balda doğal olarak bulunan çeşitli organik asitler ürünün karakteristik asidik yapısına katkıda bulunmaktadır (Kiran & Riyaz, 2026). Yüksek serbest asitlik, balda istenmeyen fermentatif değişikliklerin olası göstergelerinden biridir (Mato et al., 2003). Bununla birlikte, mevzuat sınırları içinde kalan serbest asitlik farklılıkları doğrudan fermantasyona bağlanamaz. Bu farklılıklar botanik köken ve balın doğal organik asit bileşimiyle de ilişkili olabilir (Mato et al., 2003; Kiran & Riyaz, 2026). Bu nedenle serbest asitlik değerlerinin nem, HMF ve diğer kalite parametrelerinden bağımsız olarak yorumlanması yanıltıcı olabilmektedir. Bal kalitesinin değerlendirilmesinde kullanılan bir diğer önemli parametre prolin içeriğidir. Prolin, balda bulunan başlıca serbest amino asitlerden biri olup büyük ölçüde arı kaynaklıdır ve balın olgunlaşma süreciyle ilişkilendirilmektedir (Kiran & Riyaz, 2026). Prolin miktarı bu nedenle balın olgunluğunun değerlendirilmesinde kullanılan göstergelerden biridir. Düşük prolin değerleri ise bazı durumlarda olası tağşişe ilişkin destekleyici bilgi de sağlayabilmektedir (Kiran & Riyaz, 2026; Cilavdaroğlu, 2026). Bununla birlikte prolin miktarı botanik köken, polen içeriği ve coğrafi koşullardan etkilenebildiğinden, farklı coğrafi bölgelerde üretilen ballar arasında değişkenlik gösterebilmektedir (Cilavdaroğlu, 2026). Balda bulunan enzimlerden biri olan diastazın aktivitesi de ürünün tazeliğinin ve özellikle ısıl işlemlere maruz kalıp kalmadığının değerlendirilmesinde kullanılmaktadır (Tosi et al., 2008). Diastaz sıcaklığa duyarlı olduğundan, balın uzun süre yüksek sıcaklıklarda tutulması veya uygun olmayan işleme koşullarına maruz kalması enzim aktivitesinin azalmasına neden olabilmektedir (Tosi et al., 2008). Bununla birlikte ısıl işlem sonrasında diastaz aktivitesinde kısmi geri kazanım görülebildiğinden, bu parametre ısıl geçmişin belirlenmesinde tek başına belirsiz sonuçlar verebilmektedir (Tosi et al., 2008). Bu nedenle diastaz aktivitesinin HMF miktarıyla birlikte değerlendirilmesi daha anlamlıdır. HMF, özellikle heksozların asidik ortamda dehidrasyonu sonucu oluşan bir bileşik olup taze ve uygun şartlarda saklanmış ballarda genellikle düşük düzeylerde bulunmaktadır (Shapla et al., 2018). Depolama süresinin uzaması ve yüksek sıcaklık uygulamaları HMF oluşumunu hızlandırabildiğinden bu bileşik, balın tazeliği ve ısıl geçmişinin değerlendirilmesinde ulusal ve uluslararası mevzuatta yaygın olarak kullanılan kalite göstergelerinden

biridir (Shapla et al., 2018; Codex Alimentarius Commission, 2001; Türk Gıda Kodeksi, 2020). Balın şeker kompozisyonu ise hem ürünün doğal yapısının hem de fiziksel davranışının değerlendirilmesi açısından önem taşımaktadır. Balın toplam şeker içeriğinin büyük bölümünü monosakkaritlerden fruktoz ve glukoz oluştururken sakaroz, maltoz ve diğer oligosakkaritler daha düşük miktarlarda bulunmaktadır (Kiran & Riyaz, 2026). Fruktoz ve glukozun toplam miktarı balın olgunlaşması ve doğal şeker yapısının değerlendirilmesinde kullanılırken, yüksek sakaroz değerleri balın olgunlaşmadan hasat edildiğine ya da sakaroz şurubuyla tağşiş yapıldığına işaret edebilmektedir (Guler et al., 2007; Zhang et al., 2021). Fruktoz/glukoz oranı ise balın kristalizasyon eğilimi hakkında yararlı bilgiler sağlayabilmektedir (Kiran & Riyaz, 2026). Glukozun fruktoza göre daha baskın olduğu balların daha hızlı kristalleşme eğilimi gösterebilmesi nedeniyle şeker profili, balın yalnızca mevzuata uygunluğunu değil, depolama sırasında göstereceği fiziksel davranışı anlamak bakımından da önemlidir. Türkiye, arıcılığa uygun coğrafi ve iklimsel koşulları nedeniyle dünyanın en büyük bal üreticisi ülkeleri arasında yer almaktadır (Gürbüz et al., 2020). Özellikle kısa mesafeler içerisinde önemli yükselti ve iklim farklılıklarının görüldüğü bölgelerde, bal üretim alanlarının fizikokimyasal özellikleri açısından karşılaştırılması bölgesel bal karakterizasyonu bakımından önem taşımaktadır. Artvin ili bu açıdan dikkat çekici bir coğrafi yapıya sahiptir. İl sınırları içerisinde Karadeniz etkisinin belirgin olduğu nemli vadilerden daha kurak iç kesimlere, düşük rakımlı vadi tabanlarından yüksek yayla ve plato alanlarına kadar farklı ekolojik koşullar bir arada bulunmaktadır (Batan & Özdemir, 2013; Çelik et al., 2026). Bu topoğrafik ve iklimsel heterojenlik, arıların yararlanabileceği bitkisel kaynakların ve bal üretim koşullarının kısa mesafelerde değişebilmesine olanak sağlamaktadır (Bozkuş, 2025). Dolayısıyla Artvin'in farklı lokasyonlarından elde edilen balların fizikokimyasal özelliklerinin birbirinden farklılaşması ve bu özelliklerin çevre üretim bölgeleriyle karşılaştırılması, coğrafi ve ekolojik değişkenliğin bal özelliklerine olası yansımalarının ortaya konması açısından önemlidir. Artvin ballarına ilişkin daha önce gerçekleştirilen bir çalışma, polen analiziyle monofloral olduğu belirlenen kestane ballarının fizikokimyasal özellikleri, fenolik profilleri ve antioksidan özellikleri hakkında önemli bilgiler sağlamıştır (Saral, 2023). Benzer şekilde Rize-Şenoz Vadisi'nde kestane ve yayla ballarının karşılaştırıldığı çalışmada en yüksek pH ve elektriksel iletkenlik değerleri kestane ballarında belirlenmiştir (Demir Kanbur et al., 2021). Güneydoğu Anadolu'dan toplanan 68 bal örneğinin incelendiği çalışmada ise örneklerin bir kısmının diastaz, prolin ve HMF bakımından yasal sınırları karşılamadığı bildirilmiştir (Gürbüz et al., 2020). Bununla birlikte Artvin'in kendi içerisinde farklı topoğrafik ve ekolojik özellikler gösteren lokasyonlarından elde edilen bal örneklerinin, benzer veya karşılaştırılabilir coğrafi özelliklere sahip çevre üretim alanlarıyla aynı analitik parametreler üzerinden birlikte değerlendirilmesi bölgesel karakterizasyon açısından ayrıca önem taşımaktadır. Böyle bir karşılaştırma, gözlenen farklılıkların yalnızca idari il sınırları üzerinden değil, yükselti, topoğrafya, iklim ve olası botanik kaynak farklılıkları çerçevesinde yorumlanmasına olanak sağlayabilir.

Mevcut çalışmada, Artvin ilinin farklı coğrafi ve topoğrafik koşullarını temsil eden Ardanuç-Zekeriyaköy Aksu Yaylası, Yusufeli-Erenköy, Şavşat-Ciritdüzü, Murgul-Erenköy ve Borçka-Maçahel Efeler lokasyonlarından elde edilen bal örneklerinin temel fizikokimyasal özelliklerinin belirlenmesi amaçlanmıştır. Artvin örnekleri ayrıca çevre üretim bölgelerini temsil eden Ağrı-Eleşkirt, Kars-Kağızman, Ardahan-Posof ve Rize-Hemşin örnekleriyle karşılaştırılmıştır. Bu amaçla bal örneklerinde nem içeriği, elektriksel iletkenlik, prolin miktarı, diastaz aktivitesi, HMF düzeyi, serbest asitlik ve şeker kompozisyonu standart analitik yöntemlerle belirlenmiştir. Böylece hem Artvin içerisindeki farklı üretim lokasyonlarının fizikokimyasal değişkenliğinin ortaya konması hem de Artvin ballarının çevre üretim bölgeleriyle benzerlik ve farklılıklarının değerlendirilmesi hedeflenmiştir. Elde edilen verilerin, Artvin ballarının bölgesel kalite özelliklerinin tanımlanmasına, farklı coğrafi üretim alanlarının karşılaştırılmasına ve ileride botanik kökeni de kapsayacak daha ayrıntılı karakterizasyon çalışmalarına temel oluşturması amaçlanmıştır.

MATERYAL VE METOT

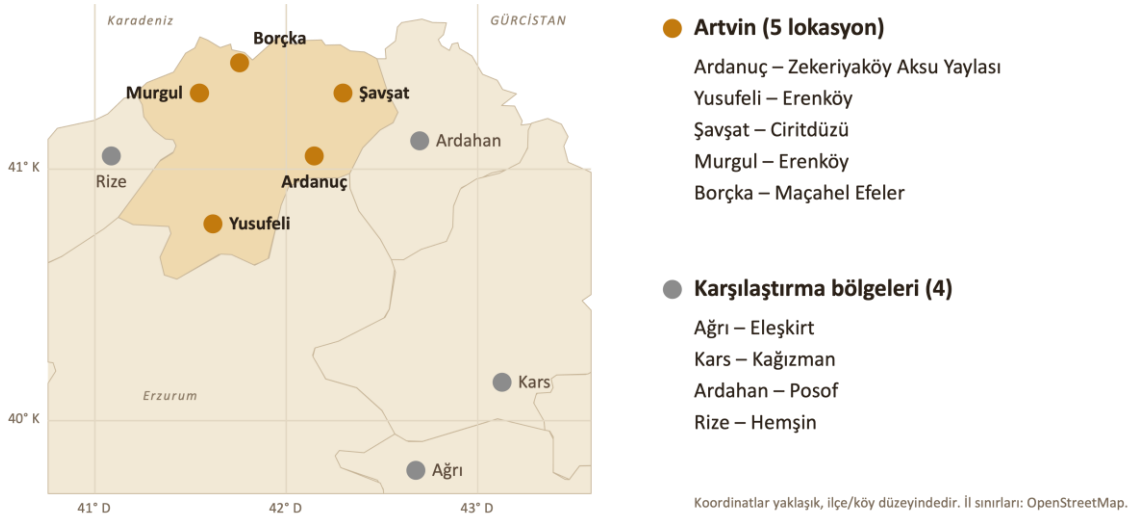
Materyal

Bu çalışmada kullanılan bal örnekleri, farklı coğrafi ve ekolojik özellikleri temsil eden Artvin ili ile çevre illerdeki üretim bölgelerinden temin edilmiştir. Artvin iline ait bal örnekleri Ardanuç ilçesi Zekeriyaköy Aksu Yaylası, Yusufeli ilçesi Erenköy, Şavşat ilçesi Ciritdüzü, Murgul ilçesi Erenköy ve Borçka ilçesi Maçahel Efeler lokasyonlarındaki yerel bal üreticilerinden sağlanmıştır. Karşılaştırma amacıyla kullanılan bal örnekleri ise Ağrı ili Eleşkirt ilçesi, Kars ili Kağızman ilçesi, Ardahan ili Posof

ilçesi ve Rize ili Hemşin ilçesindeki üreticilerden temin edilmiştir (Şekil 1). Bal örnekleri 2024 yılı sağım döneminde, her bir lokasyondan yaklaşık 200 g olacak şekilde cam kavanozlara alınarak temin edilmiştir. Örnekler analizler gerçekleştirilinceye kadar kapaklı cam kavanozlarda, 25 °C'de, doğrudan ışık ve dış ortam koşullarından korunacak şekilde muhafaza edilmiştir. Elde edilen bal numunelerinin nem, elektriksel iletkenlik, serbest asitlik, prolin miktarı, diastaz aktivitesi, hidroksimetilfurfural (HMF) içeriği ve şeker kompozisyonu analizleri örneklerin toplandığı yıl içerisinde gerçekleştirilmiştir. Her bir örneğe ait analizler üç tekrarlı olarak yürütülmüştür. Sonuçlar bu üç teknik tekrarın ortalaması olarak verilmiştir. Teknik tekrarlar bağımsız biyolojik örnekleri temsil etmediğinden verilere çıkarımsal istatistik uygulanmamıştır. Çalışma kapsamında gerçekleştirilen tüm deneysel çalışmalar Rize Gıda Kontrol Laboratuvar Müdürlüğü bünyesinde yürütülmüştür. Numunelerin hazırlanması, fizikokimyasal analizlerin gerçekleştirilmesi ve cihazlı ölçümler ilgili laboratuvarın mevcut altyapısı ve standart analiz prosedürleri kullanılarak gerçekleştirilmiştir. Çalışmada kullanılan tüm kimyasal maddeler Sigma-Aldrich ve Isolab firmalarından temin edilmiştir.

Metot

Türk Standartları Enstitüsü TS 13365/2008 – Su Muhtevası Tayini
Türk Standartları Enstitüsü TS 13366/2008 – Balda Elektrik İletkenliği Tayini
Türk Standartları Enstitüsü TS 13357/2008 – Balda Prolin Muhtevasının Tayini
Türk Standartları Enstitüsü TS 13364/2008 – Balda Diastaz Aktivitesi Tayini
Türk Standartları Enstitüsü TS 13356/2008 – Balda HMF Tayini
Türk Standartları Enstitüsü TS 13360/2008 – Balda Serbest Asit Muhtevasının Tayini
Türk Standartları Enstitüsü TS 13359/2008 – Balda Fruktoz, Glukoz, Sakaroz, Turanoz ve Maltoz Muhtevası Tayini



Şekil 1. Bal temin bölgelerinin yerleşimi

BULGULAR VE TARTIŞMA

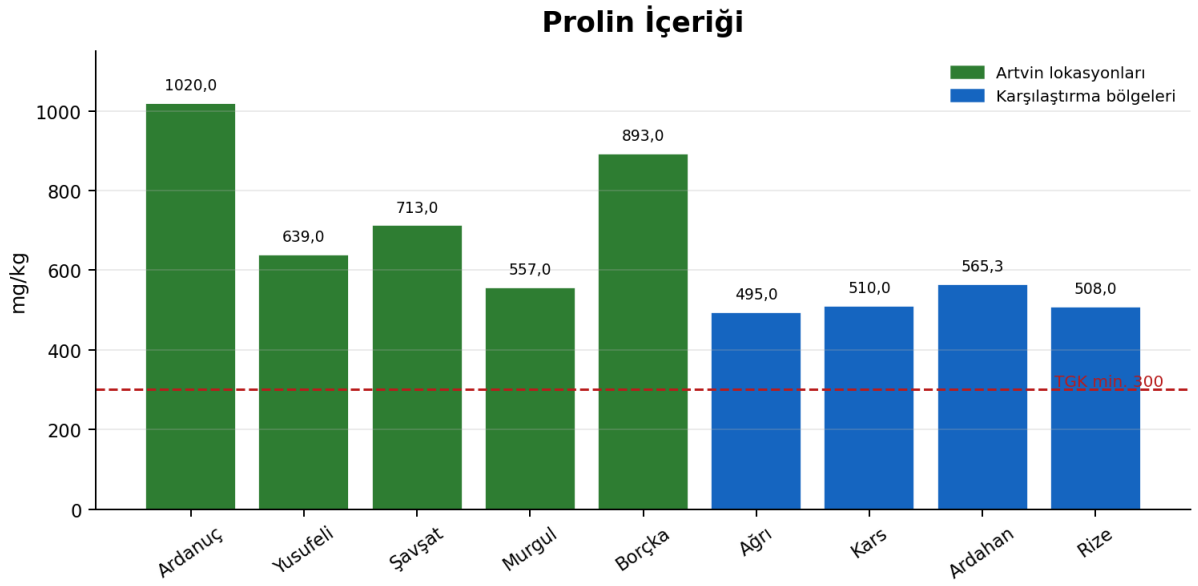
Bu çalışmada, Artvin ilinin farklı coğrafi ve ekolojik koşullarını temsil eden Ardanuç-Zekeriyaköy Aksu Yaylası, Yusufeli-Erenköy, Şavşat-Ciritdüzü, Murgul-Erenköy ve Borçka-Maçahel Efeler lokasyonlarından alınan bal örnekleri ile Ağrı-Eleşkirt, Kars-Kağızman, Ardahan-Posof ve Rize-Hemşin bölgelerinden temin edilen bal örneklerinin temel fizikokimyasal kalite özellikleri karşılaştırmalı olarak değerlendirilmiştir (Tablo 1). İncelenen parametreler prolin içeriği, diastaz aktivitesi, hidroksimetilfurfural (HMF), nem, elektriksel iletkenlik, serbest asitlik ve şeker kompozisyonunu kapsamaktadır. Elde edilen bulgular, incelenen bütün bal örneklerinin prolin, diastaz aktivitesi, HMF, nem, serbest asitlik ve şeker kompozisyonu bakımından Türk Gıda Kodeksi Bal Tebliği'nde belirtilen sınırları karşıladığını göstermiştir. Elektriksel iletkenlik değerlerinin mevzuata uygunluğunun kesin olarak değerlendirilebilmesi için ise örneklerin botanik kökenlerinin doğrulanması gerekmektedir.

Tablo 1. Bal örneklerinin temel fizikokimyasal kalite parametreleri

Lokasyon	Prolin (mg/kg)	Diastaz (Gothe)	HMF (mg/kg)	Nem (%)	İletkenlik (mS/cm)	Serbest asitlik (meq/kg)	F+G (%)	F/G
Ardanuç-Zekeriyaköy Aksu Yaylası	1020,00	31,34	3,53	15,98	0,578	43,21	68,30	1,19
Yusufeli-Erenköy	639,00	22,42	4,14	16,40	0,537	34,16	63,22	1,49
Şavşat-Ciritdüzü	713,00	22,45	2,55	15,15	1,383	32,27	62,61	1,34
Murgul-Erenköy	557,00	16,93	1,48	19,50	1,116	32,22	68,95	0,93
Borçka-Maçahel Efeler	893,00	35,97	9,31	16,30	1,026	38,93	69,13	1,19
Ağrı-Eleşkirt	495,00	25,34	1,14	17,23	0,194	15,60	70,86	1,21
Kars-Kağızman	510,00	19,33	0,66	17,77	0,227	19,73	68,21	1,30
Ardahan-Posof	565,33	13,90	0,33	16,67	0,193	14,93	69,16	1,29
Rize-Hemşin	508,00	19,14	0,41	17,70	1,089	25,67	69,38	1,26

Prolin İçeriğinin Değerlendirilmesi

Türk Gıda Kodeksi'nde prolin için kabul edilen minimum değer 300 mg/kg'dır (Türk Gıda Kodeksi, 2020). Bu çalışmada analiz edilen dokuz örneğin tamamında prolin miktarının bu değerin üzerinde bulunması, örneklerde yetersiz olgunlaşmaya işaret eden düşük prolin seviyelerinin bulunmadığını göstermektedir.

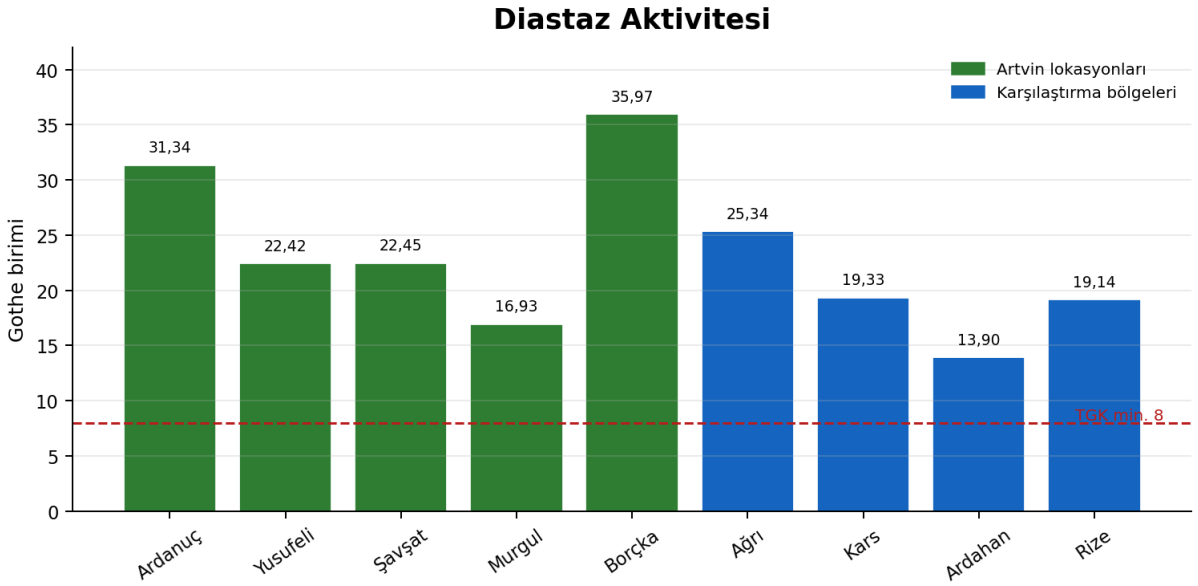


Şekil 2. Bal örneklerinin prolin içerikleri ve Türk Gıda Kodeksi minimum sınırı.

Artvin bal örneklerinde prolin içeriği 557–1020 mg/kg arasında değişmiş ve grup ortalaması 764,4 mg/kg olarak hesaplanmıştır (Şekil 1). En yüksek prolin değeri 1020 mg/kg ile Ardanuç-Zekeriyaköy

Aksu Yaylası'nda belirlenmiş, bunu 893 mg/kg ile Borçka-Maçahel Efeler ve 713 mg/kg ile Şavşat-Ciritdüzü izlemiştir. Karşılaştırma bölgelerinde ise değerler 495–565,33 mg/kg arasında daha dar bir aralıkta değişmiş ve ortalama yaklaşık 520 mg/kg olmuştur. Buna göre iki grubun ortalama prolin içerikleri arasında yaklaşık 1,5 katlık bir fark bulunmaktadır.
İncelenen bütün örneklerde prolin miktarı Türk Gıda Kodeksi'nde belirtilen alt sınırın üzerindedir. Bu nedenle lokasyonlar arasındaki prolin farkları bir kalite üstünlüğü ya da eksikliği olarak değil, örneklerin üretildiği alanların özelliklerindeki farklılıklar çerçevesinde değerlendirilmelidir. Prolin miktarı botanik köken, polen içeriği, coğrafi koşullar ve hasat zamanından etkilenebilmektedir (Cilavdaroğlu, 2026). Dolayısıyla gözlenen farklar, lokasyonlar arasındaki bitki örtüsü ve bitki çeşitliliği, topoğrafya ve iklim gibi coğrafi etkenler ile hasat dönemi farklılıklarıyla ilişkili olabilir. Mevcut çalışmada bu etkenler doğrudan ölçülmediği için söz konusu ilişkinin polen analizi ve hasat bilgilerini içeren çalışmalarla incelenmesi gerekmektedir.

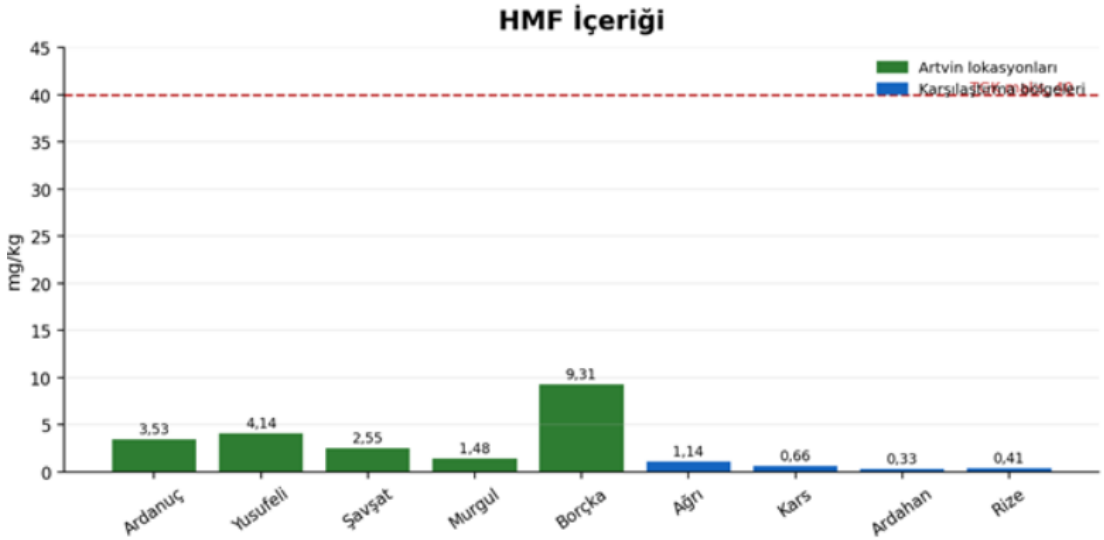
Diastaz Aktivitesinin Değerlendirilmesi
Türk Gıda Kodeksi kapsamında kabul edilen minimum diastaz aktivitesi 8 Gothe birimidir (Türk Gıda Kodeksi, 2020).



Şekil 3. Bal örneklerinin diastaz aktiviteleri ve minimum kabul sınırı.

Bu çalışmada diastaz aktivitesi bütün örneklerde söz konusu sınırın üzerinde bulunmuştur (Şekil 2). Artvin ballarında değerler 16,93 ile 35,97 Gothe arasında değişirken, karşılaştırma bölgelerinde 13,90 ile 25,34 Gothe arasında değişmiştir. Artvin örnekleri içerisinde en yüksek diastaz aktivitesi Borçka-Maçahel Efeler'de 35,97 Gothe olarak belirlenmiş, bunu 31,34 Gothe ile Ardanuç-Aksu Yaylası izlemiştir. Çevre bölgelerde en yüksek değer ise Ağrı-Eleşkirt'te 25,34 Gothe'dir. Artvin grubunun ortalaması 25,82, çevre bölgelerin ortalaması ise 19,43 Gothe olarak hesaplanmıştır.
Diastaz aktivitesi balın olgunlaşma düzeyine göre artabilmekte, ısıl işlem ve depolama koşullarına bağlı olarak da azalabilmektedir (Tosi et al., 2008; Zhang et al., 2021). Bu nedenle lokasyonlar arasındaki farklar hasat dönemi, olgunlaşma düzeyi ve hasattan analize kadar geçen süre gibi etkenlerle ilişkili olabilir. Mevcut verilere göre örneklerde düşük enzim aktivitesine veya ısıl hasara işaret eden bir bulgu bulunmamaktadır.

HMF İçeriğinin Değerlendirilmesi
Türk Gıda Kodeksi'nde HMF için kabul edilen üst sınır 40 mg/kg'dır (Türk Gıda Kodeksi, 2020).



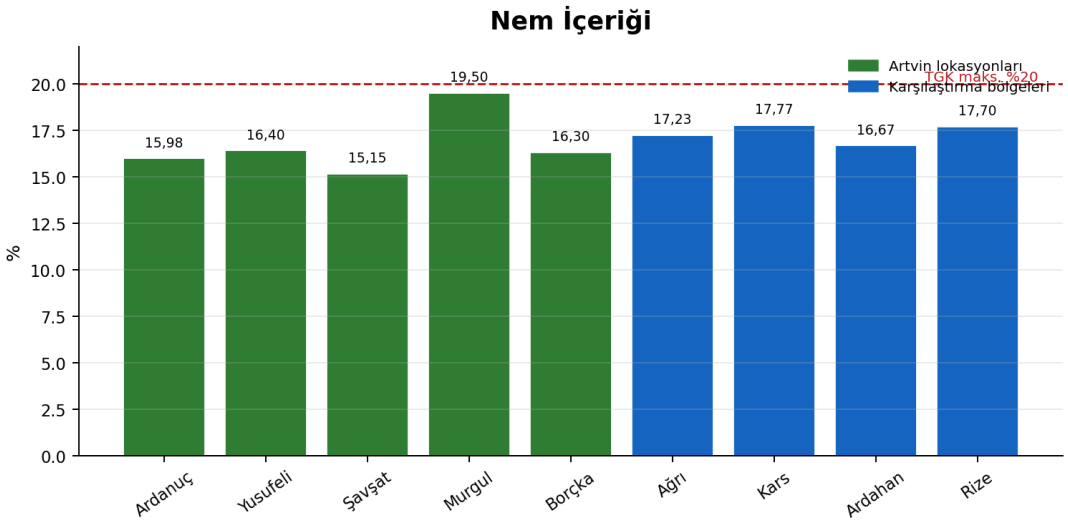
Şekil 4. Bal örneklerinin HMF içerikleri ve Türk Gıda Kodeksi maksimum sınırı.

Mevcut çalışmada bütün örneklerin HMF değerleri 10 mg/kg'ın altında bulunmuştur (Şekil 3). En düşük değer Ardahan örneğinde 0,33 mg/kg, en yüksek değer ise Borçka-Maçahel Efeler örneğinde 9,31 mg/kg'dır. Artvin örneklerinin ortalaması 4,20 mg/kg, çevre bölgelerin ortalaması ise yaklaşık 0,63 mg/kg olarak hesaplanmıştır. Her ne kadar Artvin grubunun ortalaması karşılaştırma grubundan yüksek olsa da, her iki grubun değerleri de 40 mg/kg'lık üst sınırın altındadır.

Bu nedenle gruplar arasındaki HMF farkını bir kalite kaybı ya da aşırı ısıl işlem göstergesi olarak değerlendirmek doğru olmayacaktır. Özellikle Artvin grubundaki en yüksek değer olan 9,31 mg/kg dahi kodeks üst sınırının yaklaşık dörtte birinden daha düşüktür. HMF düzeyindeki bu varyasyon, hasattan analize kadar geçen süre, sıcaklık geçmişi, balın doğal asitliği ve şeker bileşimi gibi etkenlerle ilişkili olabilir (Fallico et al., 2004; Shapla et al., 2018). HMF sonuçlarının diastaz aktivitesi ile birlikte değerlendirilmesi de önemlidir (Sajid et al., 2019). Mevcut çalışmada bütün örneklerde diastaz değerinin 8'in üzerinde olması ve HMF'nin 10 mg/kg'ın altında kalması, incelenen ballarda yoğun ısıl işleme veya uzun süreli uygunsuz depolamaya işaret eden bir fizikokimyasal bulgunun bulunmadığını desteklemektedir.

Nem İçeriğinin Değerlendirilmesi

Türk Gıda Kodeksi'nde balın nem içeriği için üst sınır %20'dir (Türk Gıda Kodeksi, 2020).



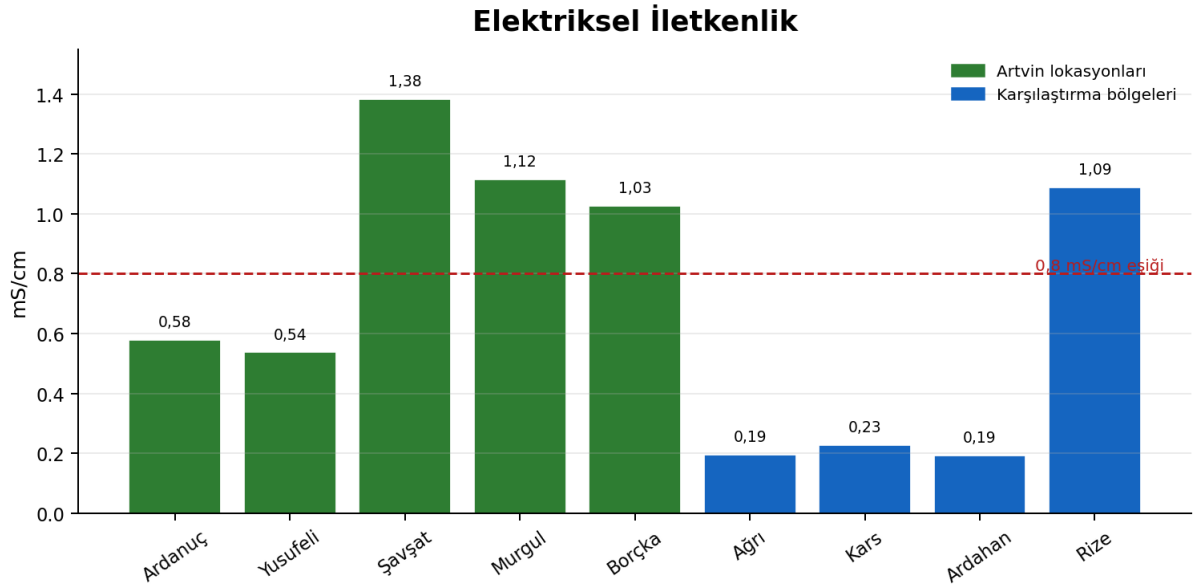
Şekil 5. Bal örneklerinin nem içerikleri ve maksimum kabul sınırı.

Çalışmada Artvin örneklerinin nem değerleri %15,15–19,50 arasında değişirken, çevre bölge örneklerinde %16,67–17,77 aralığında bulunmuştur. Bütün örneklerin nem oranı %20'lik maksimum sınırın altında kalmıştır (Şekil 4). Artvin ortalaması %16,67, çevre bölgelerin ortalaması ise %17,34'tür. Artvin örnekleri içerisinde en düşük nem %15,15 ile Şavşat-Ciritdüzü'nde, en yüksek nem ise %19,50 ile Murgul-Erenköy'de belirlenmiştir.

Murgul örneği %19,50 nem değeriyle %20 sınırına en yakın örnektir. Ancak tek başına bu değer fermantasyon olasılığı şeklinde düşünülmemelidir. Zira Murgul örneğinde HMF değerinin yalnızca 1,48 mg/kg olması ve serbest asitliğinin mevzuat sınırları içerisinde bulunması, örnekte bir bozulma göstergesi olmadığını düşündürmektedir. Ayrıca nem içeriği coğrafi kökenin yanı sıra hasat zamanı, petekteki olgunlaşma düzeyi ve üretim dönemindeki meteorolojik koşullara göre de değişebilmektedir (Rivera-Mondragón et al., 2023; Kiran & Riyaz, 2026). Bununla birlikte %19,50 nem ve 0,93 F/G oranı birlikte değerlendirildiğinde, bu örnekte depolama sırasında kristalleşme ve fermantasyon riskinin izlenmesi uygun olacaktır (Escuredo et al., 2014; Singh & Singh, 2018).

Elektriksel İletkenliğin Değerlendirilmesi

Elektriksel iletkenlik değerleri, örnekleri 0,8 mS/cm eşiğinin altında ve üstünde kalan iki gruba ayırmıştır. Türk Gıda Kodeksi'nde elektriksel iletkenlik için çiçek ballarında en fazla 0,8 mS/cm, kestane ballarında ise en az 0,8 mS/cm sınırı tanımlanmıştır (Türk Gıda Kodeksi, 2020).



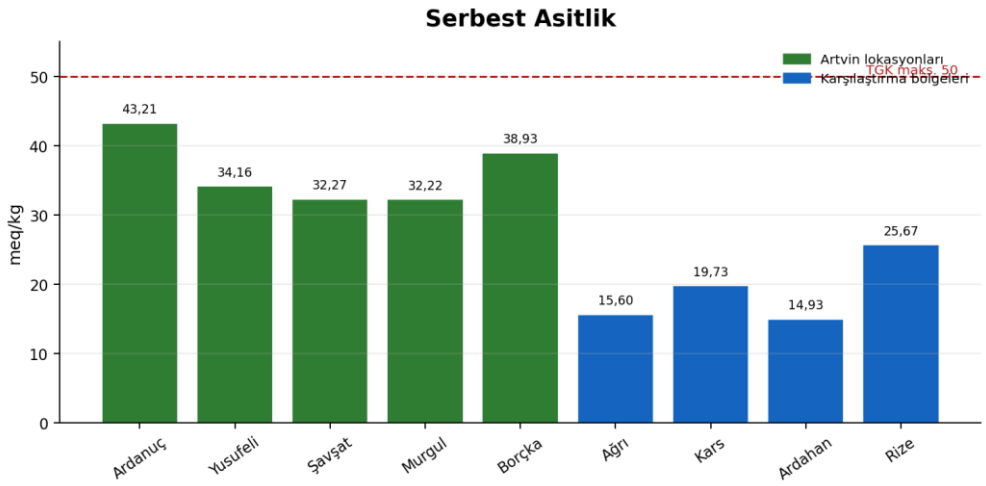
Şekil 6. Bal örneklerinin elektriksel iletkenlik değerleri ve 0,8 mS/cm eşiği

Artvin örneklerinde elektriksel iletkenlik 0,537–1,383 mS/cm arasında değişmiştir (Şekil 5). Ardanuç ve Yusufeli örneklerinin değerleri sırasıyla 0,578 ve 0,537 mS/cm ile 0,8 mS/cm'nin altında iken Şavşat, Murgul ve Borçka örneklerinde sırasıyla 1,383, 1,116 ve 1,026 mS/cm değerleri elde edilmiştir. Çevre bölgelerden Ağrı, Kars ve Ardahan örnekleri yaklaşık 0,19–0,23 mS/cm gibi düşük değerler gösterirken Rize-Hemşin örneğinde 1,089 mS/cm ölçülmüştür. Artvin grubunun ortalaması 0,93 mS/cm, çevre bölgelerin ortalaması ise 0,43 mS/cm olarak hesaplanmıştır. Kars ilinden toplanan 30 bal örneğinin incelendiği bir çalışmada elektriksel iletkenlik 0,138–0,343 mS/cm aralığında bildirilmiştir (Akpınar & Mutlu, 2025). Mevcut çalışmadaki Kars-Kağızman değeri (0,227 mS/cm) bu aralıkta yer almaktadır.

İç ve daha karasal alanları temsil eden Ağrı, Kars, Ardahan, Ardanuç ve Yusufeli örneklerinde iletkenlik genel olarak daha düşük iken Karadeniz etkisinin daha belirgin olduğu Şavşat, Murgul, Borçka ve Rize örneklerinde daha yüksek değerler gözlenmiştir. Bu durumun kestane başta olmak üzere farklı nektar ve salgı kaynaklarının katkısıyla ilişkili olması mümkündür (Girolametti et al., 2026). Ancak mevcut çalışmada polen analizi gerçekleştirilmediği için yüksek elektriksel iletkenliğe dayanarak tek başına kesin bir botanik köken tanımlaması yapılmamalıdır.

Serbest Asitliğin Değerlendirilmesi

Türk Gıda Kodeksi'nde serbest asitlik için üst sınır 50 meq/kg'dır (Türk Gıda Kodeksi, 2020).



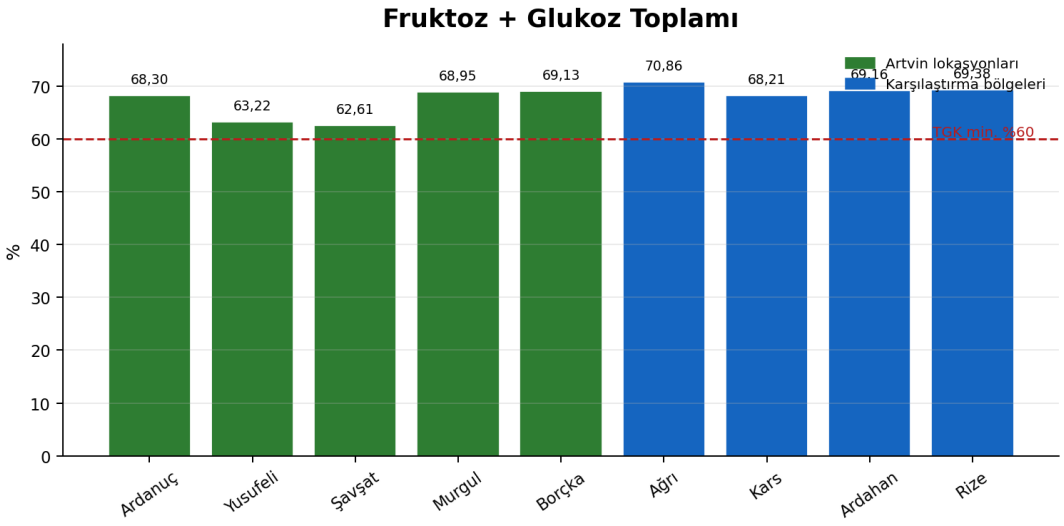
Şekil 7. Bal örneklerinin serbest asitlik değerleri ve maksimum kabul sınırı.

Mevcut çalışmada Artvin ballarında serbest asitlik değerleri 32,22–43,21 meq/kg arasında değişmiştir (Şekil 6). Buna karşılık çevre bölgelerde 14,93–25,67 meq/kg aralığı belirlenmiştir. Artvin grubunun ortalaması 36,16 meq/kg iken karşılaştırma grubunun ortalaması 18,99 meq/kg'dır. Buna göre iki grubun ortalama serbest asitlik değerleri arasında yaklaşık 1,9 katlık bir fark bulunmaktadır. Bununla birlikte bütün örnekler 50 meq/kg sınırının altında kalmıştır.

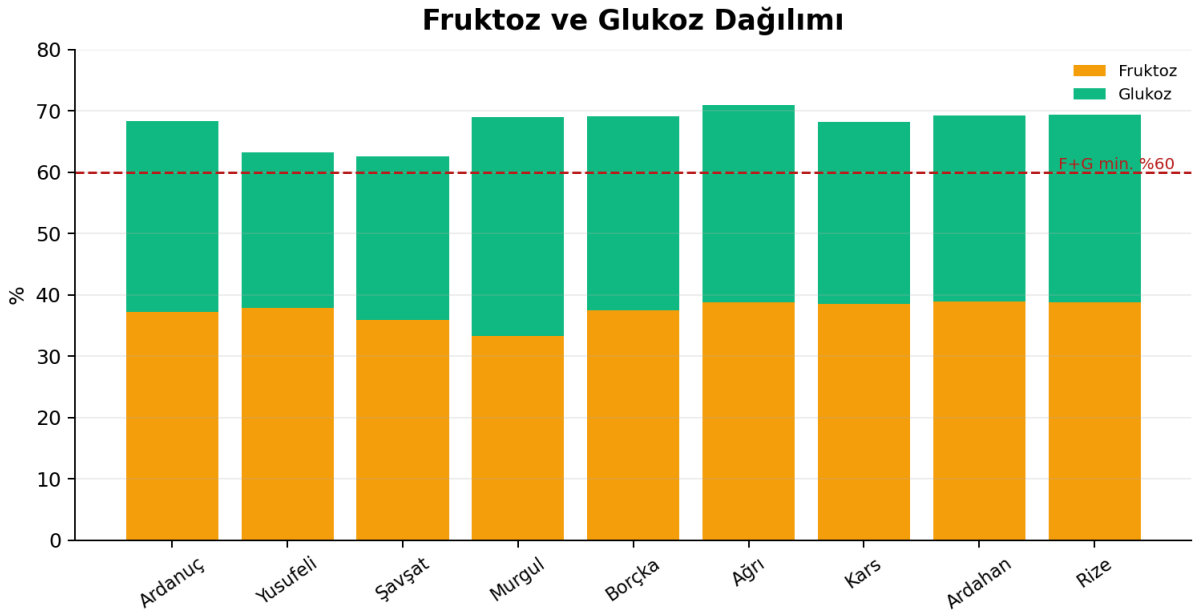
Artvin örneklerinde gözlenen yüksek serbest asitliğin fermantasyonla doğrudan ilişkilendirilmesi mevcut verilerle mümkün değildir. Bu örneklerde nem içeriği %15,15–19,50, HMF düzeyi ise 1,48–9,31 mg/kg aralığında belirlenmiş ve her iki parametre de mevzuat sınırları içerisinde kalmıştır. Bununla birlikte çalışmada maya sayısı ile etanol ve gliserol gibi fermantasyon göstergeleri ve organik asit profili belirlenmemiştir. Dolayısıyla serbest asitlikteki farklılığın fermantasyondan mı, yoksa botanik köken ve nektarın doğal organik asit bileşiminden mi kaynaklandığı mevcut bulgularla ayırt edilememektedir. Bu olası açıklamaların, söz konusu değişkenleri kapsayan ileri analizlerle araştırılması gerekmektedir.

Şeker Kompozisyonunun Değerlendirilmesi

Türk Gıda Kodeksi'nde fruktoz + glukoz toplamı için alt sınır %60, sakaroz için üst sınır ise %5'tir (Türk Gıda Kodeksi, 2020).



Şekil 8. Bal örneklerinin fruktoz + glukoz toplamları ve minimum kabul sınırı.



Şekil 9. Bal örneklerinde fruktoz ve glukoz dağılımı.

Tablo 2. Bal örneklerinin şeker kompozisyonu

Lokasyon	Fruktoz (%)	Glukoz (%)	Sakaroz (%)	Maltoz (%)	F+G (%)	F/G
Ardanuç	37,15	31,15	ND	1,29	68,30	1,19
Yusufeli	37,80	25,42	0,02	1,75	63,22	1,49
Şavşat	35,90	26,71	ND	1,83	62,61	1,34
Murgul	33,26	35,69	0,02	1,01	68,95	0,93
Borçka	37,50	31,63	0,15	0,53	69,13	1,19
Ağrı	38,76	32,10	ND	1,69	70,86	1,21
Kars	38,56	29,65	0,65	0,98	68,21	1,30
Ardahan	38,91	30,25	ND	1,12	69,16	1,29
Rize	38,71	30,67	ND	0,11	69,38	1,26

Çalışmada fruktoz + glukoz toplamı bütün örneklerde %60'ın üzerinde bulunmuştur (Şekil 7, Tablo 2). En düşük değer %62,61 ile Şavşat-Ciritdüzü'nde, en yüksek değer ise %70,86 ile Ağrı-Eleşkirt örneğinde tespit edilmiştir. Artvin örneklerinde ortalama fruktoz + glukoz miktarı %66,44, çevre bölgelerde ise %69,40 olarak hesaplanmıştır. Bütün örneklerin bu parametre bakımından mevzuat gerekliliklerini karşıladığı görülmektedir. Ardanuç, Şavşat, Ağrı, Ardahan ve Rize örneklerinde sakaroz tespit edilmezken diğer örneklerde %0,02–0,65 aralığında değerler belirlenmiştir. Bu değerlerin tamamı %5'lik üst sınırın altındadır. Maltoz miktarı ise %0,11 (Rize-Hemşin) ile %1,83 (Şavşat-Ciritdüzü) arasında değişmiş ve bütün örneklerde %4'lük üst sınırın altında kalmıştır.

Fruktoz/glukoz oranı örneklerin kristalizasyon eğiliminin değerlendirilmesinde yararlı bilgiler sağlamaktadır (Escuredo et al., 2014). Çalışmada F/G oranı genel olarak 0,93–1,49 arasında değişmiştir (Şekil 8). Murgul-Erenköy örneği 0,93 oranıyla diğer örneklerden ayrılmaktadır. Bu örnekte glukoz (%35,69) fruktozdan (%33,26) daha yüksek bulunmuştur. Bu kompozisyon, diğer koşullar aynı olduğunda, daha yüksek kristalizasyon eğilimiyle uyumlu olabilir. Buna karşılık Yusufeli-Erenköy örneğinde F/G oranının 1,49 olması, fruktozun glukoza göre daha baskın olduğu bir şeker profilini göstermektedir.

SONUÇ

Bu çalışma, Artvin'in farklı üretim alanlarından elde edilen bal örneklerinin prolin, serbest asitlik ve elektriksel iletkenlik başta olmak üzere bazı fizikokimyasal özellikler bakımından değişkenlik gösterdiğini ortaya koymuştur. Artvin örneklerindeki bu değişkenlik, diğer illerden temin edilen örneklerle birlikte değerlendirildiğinde, balın fizikokimyasal özelliklerinin yalnızca il veya bölge ölçeğinde açıklanamayacağını göstermektedir. İncelenen örneklerin prolin, diastaz aktivitesi, HMF, nem, serbest asitlik ve şeker kompozisyonu bakımından mevzuatta belirtilen sınırları karşılaması, örnekler arasındaki farklılıkların mevzuata uygunluktan ziyade üretim alanlarının botanik ve ekolojik özellikleriyle ilişkili olabileceğini düşündürmektedir. Elektriksel iletkenlik değerlerinin mevzuata uygunluğunun kesin olarak değerlendirilebilmesi için ise örneklerin botanik kökenlerinin belirlenmesi gerekmektedir.

Artvin'in farklı üretim alanlarından elde edilen örneklerin, mevzuat sınırları içinde kalmalarına rağmen farklı fizikokimyasal değerler göstermesi, il içerisinde değişen coğrafi, topoğrafik ve iklimsel koşulların şekillendirdiği bitki çeşitliliğinin balın bileşimi üzerinde etkili olabileceğine işaret etmektedir. Bununla birlikte örneklerin botanik kökenleri belirlenmediğinden, gözlenen değişkenliğin bitki çeşitliliğiyle ilişkisi mevcut verilerle doğrudan ortaya konulamamaktadır.

Gelecekte farklı üretim alanlarından, üreticilerden ve üretim yıllarından alınacak bağımsız örneklerde melissopalinolojik analizlerin fizikokimyasal verilerle birlikte değerlendirilmesi, botanik kökenin gözlenen değişkenlikteki rolünün daha güvenilir biçimde açıklanmasına katkı sağlayacaktır. Bu kapsamda mevcut bulgular, Artvin ballarının bölgesel özelliklerinin belirlenmesine yönelik daha kapsamlı çalışmalar için başlangıç verisi sunmaktadır.

TEŞEKKÜR

Bu çalışma kapsamında bal numunelerini temin eden tüm üreticilerimize ve Rize Gıda Kontrol Laboratuvarı Müdürlüğü çalışanlarına teşekkür ediyoruz.

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SPREAD AND HOST STATUS OF THE PLANT PARASITE VISCUM ALBUM L. IN HAZELNUT ORCHARDS IN ORDU AND GİRESUN

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Abstract

Mistletoe (*Viscum album* subsp. *album* L.) is a perennial, hemi-parasitic plant that can grow on various tree species and sustains itself by obtaining water and mineral nutrients from its host plants. Türkiye is one of the natural distribution areas of the species, where it occurs on various agricultural and forest tree species as a host. By utilizing the water and nutrient resources of its hosts, mistletoe may cause reduced shoot development, weakening of branches, and consequently yield losses, particularly under heavy infestations. Nevertheless, mistletoe also has an important ethnobotanical significance in rural communities due to its traditional uses and cultural value in local beliefs. In Türkiye, the occurrence of *V. album* on hazelnut (*Corylus avellana* var. *avellana* L.) was first reported in Düzce Province in the Western Black Sea Region. Therefore, this study investigated the distribution and host status of the species in hazelnut orchards in Ordu and Giresun provinces. Following the initial detection during hazelnut harvesting in 2026 in Hisarkaya Village, Bulancak District, Giresun Province, a rapid survey was conducted in the surrounding area along east–west and north–south directions, covering a total of 60 hazelnut orchards. *V. album* was detected in 5 of the surveyed orchards, occurring on a total of 11 hazelnut clumps. The occurrence of mistletoe particularly on hazelnut clumps located near apple and pear trees in hazelnut orchards suggests that surrounding host trees and bird species may play a role in the distribution of the species. In addition, mistletoe was detected on various host species in the study area, including apple, pear, alder, linden, and pine. Local people recognize mistletoe by several vernacular names, including “purç,” “çeküm,” “gökçe,” “gevele,” and “gövelek,” and traditionally use it for the treatment of diabetes, hypertension, cardiovascular disorders, rheumatism, and pain, as well as for animal feed and natural adhesive. The findings indicate that, following the first report from Düzce, Ordu and Giresun provinces represent the second region where the host status of hazelnut for *V. album* has been documented. Considering the species’ potential for further spread, comprehensive surveys of hazelnut orchards, identification of infested areas, and the development of appropriate management strategies are recommended.

Keywords: Mistletoe, *Viscum album*, Hazelnut, Ordu, Giresun.

COMPARISON OF ROUTINE HEMATOLOGICAL PARAMETERS AND HEMATOLOGICAL INFLAMMATORY INDICES IN PAIRED BLOOD SAMPLES COLLECTED IN K_2EDTA AND LITHIUM HEPARIN TUBES FROM HEALTHY RATS

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ABSTRACT
This study compared complete blood count (CBC) parameters and hematological inflammatory indices in paired blood samples anticoagulated with dipotassium ethylenediaminetetraacetic acid (K_2EDTA) or lithium heparin (Li-heparin) from healthy rats and assessed agreement between the measurements. Fifteen healthy female Wistar Albino rats were included. Blood from each rat was divided equally between standard K_2EDTA and Li-heparin tubes and analyzed immediately using a Mindray BC-5000 Vet hematology analyzer. The neutrophil-to-lymphocyte ratio (NLR), monocyte-to-lymphocyte ratio (MLR), platelet-to-lymphocyte ratio (PLR), systemic immune-inflammation index (SII), systemic inflammation response index (SIRI), and aggregate index of systemic inflammation (AISI) were calculated from absolute neutrophil, lymphocyte, monocyte, and platelet counts. Paired data were evaluated using parametric or nonparametric paired tests, effect sizes, intraclass correlation coefficients [ICC(A,1)], and Bland-Altman analysis. Most leukocyte parameters were comparable between anticoagulants, but the absolute lymphocyte count was lower in K_2EDTA samples ($p < 0.05$). Red blood cell count, hemoglobin concentration, and hematocrit were also lower in K_2EDTA samples ($p \leq 0.01$). All platelet parameters differed significantly between anticoagulants. Platelet count (PLT), mean platelet volume (MPV), and plateletcrit (PCT) were higher, whereas platelet distribution width (PDW) was lower in K_2EDTA samples, with large effect sizes ($p \leq 0.001$). Among the hematological inflammatory indices, PLR ($p \leq 0.001$) and SII ($p < 0.01$) were higher in K_2EDTA samples, whereas NLR, MLR, SIRI, and AISI were comparable. Good ICC point estimates for PLT, PLR, and SII were accompanied by positive bias. Agreement was poor for MPV and PDW and moderate for PCT. These findings indicate that anticoagulant choice primarily affects platelet parameters and that these differences may be reflected in PLR and SII values. Therefore, the same anticoagulant should be used throughout a rat study or monitoring protocol, and the anticoagulant type should be reported explicitly.
Keywords: K_2EDTA, Lithium Heparin, Complete Blood Count, Hematological Inflammatory Indices, Rats

ÖZET
Bu çalışmada, sağlıklı ratlardan alınan ve dipotasyum etilendiamintetraasetik asit (K_2EDTA) veya lityum heparin (Li-heparin) ile antikoagüle edilen eşleştirilmiş kan örneklerinde hemogram parametreleri ile hematolojik inflamasyon indekslerinin karşılaştırılması ve ölçümler arasındaki uyumun değerlendirilmesi amaçlandı. Çalışmaya 15 sağlıklı dişi Wistar Albino rat dahil edildi. Her rattan alınan kan, standart K_2EDTA ve lityum heparin tüplerine eşit hacimlerde aktarıldı ve Mindray BC-5000 Vet hematoloji analizöründe bekletilmeden analiz edildi. Mutlak nötrofil, lenfosit, monosit ve trombosit sayıları kullanılarak nötrofil/lenfosit oranı (NLR), monosit/lenfosit oranı (MLR), trombosit/lenfosit oranı (PLR), sistemik immün-inflamasyon indeksi (SII), sistemik inflamasyon yanıt indeksi (SIRI) ve agregat sistemik inflamasyon indeksi (AISI) hesaplandı. Eşleştirilmiş veriler parametrik veya parametrik olmayan eşleştirilmiş testler, etki büyüklükleri, sınıf içi korelasyon katsayıları [ICC(A,1)] ve Bland-Altman analiziyle değerlendirildi. Lökosit parametrelerinin çoğu iki antikoagülanda benzerdi, ancak mutlak lenfosit sayısı K_2EDTA'lı örneklerde daha düşüktü ($p < 0.05$). Eritrosit sayısı, hemoglobin konsantrasyonu ve hematokrit de K_2EDTA'lı örneklerde daha düşük bulundu ($p \leq 0.01$). Trombosit parametrelerinin tamamı antikoagülanlar arasında anlamlı farklılık gösterdi. Trombosit sayısı (PLT), ortalama trombosit hacmi (MPV) ve plateletkrit (PCT) K_2EDTA'lı örneklerde daha yüksek, trombosit dağılım genişliği (PDW) ise daha düşüktü ve bu parametreler için büyük etki büyüklükleri belirlendi ($p \leq 0.001$). Hematolojik inflamasyon indekslerinden PLR ($p \leq 0.001$) ve SII ($p < 0.01$) K_2EDTA'lı örneklerde daha yüksek bulunurken NLR, MLR, SIRI ve AISI benzerdi. PLT, PLR ve SII için iyi düzeyde ICC nokta tahminlerine pozitif yanlılık eşlik etti. Uyum MPV ve PDW için zayıf, PCT için orta düzeydeydi. Bulgular, antikoagülan seçiminin öncelikle trombosit parametrelerini etkilediğini ve bu

farklılıkların PLR ve SII değerlerine yansıyabildiğini göstermektedir. Bu nedenle, rat çalışmalarında veya izlem süreçlerinde aynı antikoagülan kullanılmalı ve antikoagülan türü açıkça raporlanmalıdır.
Anahtar Kelimeler: K_2EDTA, Lityum Heparin, Tam Kan Sayımı, Hematolojik Yangı İndeksleri, Rat

INTRODUCTION

Blood is a dynamic biological fluid composed of erythrocytes, leukocytes, and platelets suspended in plasma (Qiu, Myers, and Lam 2019). These components contribute to fundamental physiological processes such as metabolism, the immune response, and hemostasis (Korelidou et al. 2026). Hemogram or complete blood count (CBC); is a fundamental hematological analysis that provides information about red blood cell (RBC), white blood cell (WBC), and platelet (PLT) counts, as well as hemoglobin (HGB) concentration, hematocrit (HCT), red blood cell indices, white blood cell differential counts, and platelet indices (Akorsu et al. 2023). CBC testing is common in human and veterinary medicine and, when interpreted together with clinical examination, contributes to disease diagnosis, prognosis, and the monitoring of therapeutic response (Korelidou et al. 2026). In routine practice, automated hematology analyzers enable CBC parameters to be measured rapidly and reproducibly. However, the validity and CBC results depend not only on the performance of the analyzer but also on proper sample identification, collection, processing, transport, and storage procedures prior to analysis (Braun et al. 2015; Vap et al. 2012).

The choice of anticoagulant, one of these preanalytical factor, is important for the analysis of whole blood samples without clotting (Braun et al. 2015; Vap et al. 2012). Ethylenediaminetetraacetic acid (EDTA), which is widely preferred in routine hematological analyses, prevents coagulation by chelating the calcium necessary for clotting and relatively well preserves the morphology of blood cells (Banfi, Salvagno, and Lippi 2007). The International Council for Standardization in Hematology (ICSH) recommends the use of dipotassium EDTA (K_2EDTA) in samples collected for the counting and sizing of blood cells. (England et al. 1993). The anticoagulant effect of heparin is dependent on a specific pentasaccharide structure that binds to antithrombin, thereby enhancing this proteins inhibitory activity against coagulation proteases, primarily factor Xa and thrombin (Hogwood et al. 2023). Although Li-heparin is extensively used in biochemical analyses, it may not yield results comparable to K_2EDTA in hematological measurements. In a study that evaluated rat samples treated with K_2EDTA and Li-heparin, it was reported that most hematological parameters were influenced by the type of anticoagulant, that the most significant difference was observed in platelet count, and that results consistent with platelet aggregation were detected in a large number of samples treated with heparin (Moorhead et al. 2016). Therefore, it may not be appropriate to directly substitute hematological results obtained from samples treated with Li-heparin for those obtained from samples treated with K_2EDTA. Since the effect of anticoagulants on hematological measurements may vary depending on the animal species and the analytical system used, the results should be interpreted with these factors in consideration. (Braun et al. 2015; Moorhead et al. 2016).

Comparative studies indicate that the effects of anticoagulant choice vary across hematological parameters. In healthy rats, sodium citrate yielded lower total leukocyte and absolute neutrophil counts than K_3EDTA or lithium heparin, whereas red blood cell counts were similar across the three anticoagulants (Ali et al. 2020). In healthy cats, it has been reported that the red blood cell count, hematocrit, hemoglobin, mean corpuscular volume, and neutrophil count in samples first collected in a Li-heparin tube and then transferred to an EDTA tube within a short period of time are generally similar to those in standard EDTA samples. However, the correlation between automated platelet counts obtained from 0.5 mL samples collected directly into an EDTA tube or transferred from a Li-heparin tube to an EDTA tube and those from a standard 1.3 mL EDTA sample was found to be poorly correlated (Norsworthy, Cook, and Lanier 2021). In goats, no significant differences related to the anticoagulant were detected in measurements taken within the first two hours of samples containing EDTA and heparin. In contrast, it has been reported that many hematological parameters decreased after 24 and 48 hours of storage, and that these changes were more pronounced in samples stored at 25 °C compared to those stored at 4°C (Roy et al. 2024). These results indicate that the effect of anticoagulants on hematological parameters may vary depending on the animal species, storage conditions, and the analytical system used. Therefore, the impact of anticoagulant choice should be considered not only in terms of directly measured hematological parameters but also in terms of inflammation indices calculated from these parameters.

In recent years, hematological inflammatory indices that can be calculated from routine CBC data without additional laboratory testing have attracted increasing interest in both human and veterinary medicine. These indices include the neutrophil-to-lymphocyte ratio (NLR), monocyte-to-lymphocyte ratio (MLR), platelet-to-lymphocyte ratio (PLR), systemic immune-inflammation index (SII), systemic inflammation response index (SIRI), and aggregate index of systemic inflammation (AISI) (Dugăeşescu et al. 2025; Erturk, Ozturk, and Ozdemir 2026). These indices, calculated from CBC data, are readily accessible markers associated with inflammatory status and have been investigated for their potential roles in aiding diagnosis, monitoring disease activity, predicting prognosis, and evaluating treatment response across a range of diseases (Dugăeşescu et al. 2025). In addition to their primary role in hemostasis, platelets interact with leukocytes and release various cytokines and chemokines. Through these functions, they contribute to the recruitment of neutrophils, monocytes, and lymphocytes to sites of inflammation and to the regulation of immune responses (Maouia et al. 2020; Sonmez and Sonmez 2017). These roles of platelets in immune and inflammatory processes provide a biological rationale for using platelet counts in the calculation of indices such as PLR, SII, and AISI. Nevertheless, the diagnostic or prognostic performance of these indices for a specific disease may be limited when used solely. (Dugăeşescu et al. 2025; Islam, Satici, and Eroglu 2024). Since similar changes can be observed in different diseases, they must be interpreted with consideration of the animal species, population characteristics, and clinical context. (Dugăeşescu et al. 2025; Erturk et al. 2026). The reporting of reference ranges for NLR, MLR, PLR, SII, SIRI, and AISI in healthy cats highlights the need for species-specific evaluation in veterinary medicine (Erturk et al. 2026). Since these indices are calculated directly using absolute cell counts, measurement variations due to anticoagulants may also be apparent in the index results. For example, changes in platelet count may affect the PLR, SII, and AISI, while changes in monocyte count may affect the MLR, SIRI, and AISI. Therefore, it is important to assess the combined effects of K_2EDTA and Li-heparin on both blood basic hematological measures and the inflammation indices calculated from these parameters.

The effects of K_2EDTA and Li-heparin on routine hematological parameters in rats have been previously compared (Moorhead et al. 2016). However, information remains limited regarding the effects of K_2EDTA and lithium heparin on the NLR, MLR, PLR, SII, SIRI, and AISI derived from complete blood count parameters, particularly when these indices are evaluated collectively in paired samples obtained from the same animals. A paired-sample design allows each rat to serve as its own control, thereby reducing the influence of interindividual variability on the comparison. Therefore, this study aimed to compare routine hematological parameters and the hematological inflammatory indices NLR, MLR, PLR, SII, SIRI, and AISI in paired blood samples obtained concurrently from healthy female Wistar albino rats and transferred into K_2EDTA and lithium heparin tubes, and to assess agreement between the measurements obtained with the two anticoagulants.

MATERIALS AND METHODS

Ethical Approval

This study was approved by the Yozgat Bozok University Local Ethics Committee for Animal Experiments (meeting date: 4 August 2026; meeting no. 2026/6; decision no. 6).

Animals

Fifteen healthy female Wistar albino rats, aged 8–10 weeks and weighing 200–250 g, were obtained from the Experimental Research Application and Research Center of Yozgat Bozok University. The animals were housed in standard cages under controlled environmental conditions of 22 ± 2 °C, 50–60% relative humidity, and a 12 h light/12 h dark photoperiod. Standard pelleted rat feed and drinking water were provided ad libitum.

Blood Sample Collection

Before blood collection, anesthesia was induced by intramuscular administration of ketamine hydrochloride (100 mg/kg) and xylazine hydrochloride (10 mg/kg). Adequate anesthetic depth was confirmed by the absence of the pedal withdrawal reflex and response to a noxious stimulus, together with reduced muscle tone. Blood was then collected by terminal cardiac puncture. Blood obtained from each rat was transferred into two separate 13 × 75 mm tubes, one containing K_2EDTA and the other Li-

heparin, with each tube filled to the level specified by the manufacture. The order in which the tubes were filled was alternated among the rats to minimize any potential serial effects.

Hematological Analysis

The CBC was performed using the analysis mode specified by the manufacturer for rats on the Mindray BC-5000 Vet automated hematology analyzer. Before analysis, the samples were carefully mixed to provide homogeneity. The results of the CBC, including red blood cell count, hemoglobin concentration, hematocrit, red blood cell indices, total and differential white blood cell counts, platelet count, and platelet indices, were recorded.

Hematological Inflammation Indices

Hematological inflammation indices were calculated using the absolute counts of neutrophils (NEU), lymphocytes (LYM), monocytes (MON), and platelets (PLT) according to the following formulas (Erturk et al. 2026):

Neutrophil-to-lymphocyte ratio (NLR)=NEU/LYM
Monocyte-to-lymphocyte ratio (MLR)=MON/LYM
Platelet-to-lymphocyte ratio (PLR)=PLT/LYM
Systemic immune-inflammation index (SII)=(NEU×PLT)/LYM
Systemic inflammation response index (SIRI)=(NEU×MON)/LYM
Aggregate index of systemic inflammation (AISI)=(NEU×MON×PLT)/LYM

All absolute cell counts were expressed in $10^3/\mu L$. NLR, MLR, and PLR are dimensionless ratios. The units were $10^3/\mu L$ for SII and SIRI and $(10^3/\mu L)^2$ for AISI.

Statistical Analysis

Sample size was determined using G*Power version 3.1.9.7 based on a two-tailed paired-samples t test. With an assumed effect size of $d^z = 0.80$, a significance level of $\alpha = 0.05$, and a statistical power of $1-\beta = 0.80$, the minimum required sample size was calculated as 15 animals. The statistical power corresponding to this sample size was 0.821 (Faul et al. 2009). Statistical analyses were performed using IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA).

Each rat was considered an independent experimental unit. Measurements obtained from K_2EDTA and lithium heparin samples collected from the same rat were treated as paired observations. Paired differences were calculated as K_2EDTA minus lithium heparin.

Selection of the statistical test was based on the distribution of the paired within-rat differences rather than the distribution of the raw K_2EDTA and Li-heparin values. The normality of the paired differences was assessed using the Shapiro-Wilk test. Paired differences with a normal distribution were analyzed using the paired-samples t test, whereas those not normally distributed were analyzed using the Wilcoxon signed-rank test. Variables analyzed using the paired-samples t test were presented as mean ± standard deviation, and those analyzed using the Wilcoxon signed-rank test were presented as median (25th-75th percentiles).

For the paired-samples t test, effect size was calculated as Cohen's d^z by dividing the mean paired difference by the standard deviation of the paired differences. For the Wilcoxon signed-rank test, effect size was calculated using the formula $r = |Z|/\sqrt{N}$, where N represents the number of paired observations. Agreement between K_2EDTA and Li-heparin measurements was evaluated using the intraclass correlation coefficient based on a two-way mixed-effects model, an absolute-agreement definition, and a single-measure approach [ICC(A,1)], together with its 95% confidence interval. ICC point estimates were classified as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), or excellent (>0.90) agreement (Koo and Li 2016).

Systematic bias and agreement between individual measurements were further evaluated using Bland-Altman analysis. The mean paired difference was defined as the bias, and the 95% limits of agreement were calculated as the bias±1.96×the standard deviation of the paired differences. In the Bland-Altman plots generated for selected parameters, the mean of the K_2EDTA and Li-heparin measurements was plotted on the x-axis, and the K_2EDTA minus Li-heparin difference was plotted on the y-axis (Bland and Altman 1986). Results of the conventional Bland-Altman analysis were interpreted cautiously when the paired differences were not normally distributed.

No adjustment was applied for multiple testing. All tests were two-sided, and $p < 0.05$ was considered statistically significant. Significance levels were indicated as *$p < 0.05$, **$p < 0.01$, and ***$p \leq 0.001$.

RESULTS

Paired K_2EDTA and Li-heparin measurements from 15 rats were evaluated. Of the leukocyte parameters, only the absolute lymphocyte count was lower in K_2EDTA samples ($p < 0.05$). Total WBC count, absolute NEU, MON, EOS, and BAS counts, and differential leukocyte percentages did not differ significantly between the two anticoagulants ($p > 0.05$).

RBC, HGB, HCT, MCH, and RDW-CV values were lower, whereas MCHC was higher, in K_2EDTA samples ($p < 0.05$). MCV and RDW-SD did not differ significantly between the anticoagulants ($p > 0.05$).

All platelet parameters differed significantly between the anticoagulants. PLT, MPV, and PCT values were higher, whereas PDW was lower, in K_2EDTA samples ($p \leq 0.001$).

PLR and SII were the only hematological inflammatory indices that differed significantly between the anticoagulants, with both showing higher values in K_2EDTA samples. The difference was significant at $p \leq 0.001$ for PLR and $p < 0.01$ for SII. NLR, MLR, SIRI, and AISI did not differ significantly between the anticoagulants ($p > 0.05$). Descriptive statistics, p values, and effect sizes for all parameters are presented in Table 1.

Table 1. Comparison of hematological parameters and hematological inflammatory indices in paired blood samples collected into K_2EDTA and lithium heparin tubes (n = 15 rats).

Parameter	K_2EDTA	Li-heparin	p-value	Effect size
Leukocyte parameters				
WBC (10^3/µL)	5.61 ± 1.77	5.74 ± 1.83	>0.05	$d_z = -0.353$
NEU (10^3/µL)	1.44 ± 0.69	1.46 ± 0.65	>0.05	$d_z = -0.344$
LYM (10^3/µL)	3.56 (2.85-4.52)	3.77 (2.87-4.71)	<0.05*	r = 0.543
MON (10^3/µL)	0.36 ± 0.16	0.36 ± 0.20	>0.05	$d_z = -0.096$
EOS (10^3/µL)	0.04 ± 0.04	0.04 ± 0.04	>0.05	$d_z = -0.158$
BAS (10^3/µL)	0.00 (0.00-0.00)	0.00 (0.00–0.00)	>0.05	r = 0.258
NEU (%)	25.37 ± 6.71	25.31 ± 6.04	>0.05	$d_z = 0.051$
LYM (%)	67.60 ± 7.21	67.91 ± 7.03	>0.05	$d_z = -0.175$
MON (%)	6.28 ± 1.75	5.95 ± 2.00	>0.05	$d_z = 0.247$
EOS (%)	0.70 (0.20–1.20)	0.90 (0.20–1.30)	>0.05	r = 0.028
BAS (%)	0.00 (0.00–0.10)	0.00 (0.00–0.00)	>0.05	r = 0.365
Erythrocyte Parameters				
RBC (10^6/µL)	6.33 ± 0.58	6.48 ± 0.64	≤0.001***	$d_z = -1.057$
HGB (g/dL)	12.87 ± 0.79	13.07 ± 0.91	<0.01**	$d_z = -0.975$
HCT (%)	36.55 ± 2.29	37.45 ± 2.55	≤0.001***	$d_z = -1.030$
MCV (fL)	58.10 ± 4.06	58.06 ± 4.11	>0.05	$d_z = 0.147$
MCH (pg)	20.30 (19.50–21.30)	20.40 (19.40–20.80)	<0.05*	r = 0.566
MCHC (g/L)	352.13 ± 7.29	348.87 ± 5.55	<0.05*	$d_z = 0.609$
RDW-CV (%)	15.83 ± 3.89	16.01 ± 3.89	<0.05*	$d_z = -0.635$
RDW-SD (fL)	37.89 ± 9.95	38.33 ± 9.76	>0.05	$d_z = -0.553$
Platelet parameters				
PLT (10^3/µL)	909 (774–1017)	779 (514–925)	≤0.001***	r = 0.829

Parameter	K_2EDTA	Li-heparin	p-value	Effect size
MPV (fL)	6.00 (5.70–6.10)	5.40 (5.00–6.00)	<0.001***	r = 0.856
PDW (fL)	15.27 ± 0.23	15.75 ± 0.38	<0.001***	d_z = −1.461
PCT (mL/L)	5.22 (4.69–5.77)	4.16 (3.37–4.81)	<0.001***	r = 0.880
Hematological Inflammation Indices				
NLR	0.378 (0.289–0.485)	0.358 (0.279–0.490)	>0.05	r = 0.154
MLR	0.094 ± 0.029	0.091 ± 0.036	>0.05	d_z = 0.153
PLR	212.21 (171.24–285.67)	197.24 (138.33–254.85)	≤0.001***	r = 0.836
SII (10^3/μL)	315.10 (249.85–415.67)	279.91 (195.27–368.41)	<0.01**	r = 0.807
SIRI (10^3/μL)	0.143 ± 0.086	0.148 ± 0.111	>0.05	d_z = −0.146
AISI [(10^3/μL)^2]	116.45 ± 75.07	104.41 ± 79.70	>0.05	d_z = 0.496

Note: *Data are presented as mean ± standard deviation for variables whose paired differences were normally distributed and as median (25th–75th percentiles) for the remaining variables. Comparisons were performed using the paired-samples t test or the Wilcoxon signed-rank test, as appropriate. *p < 0.05, **p < 0.01, and ***p ≤ 0.001. d_z denotes Cohen's effect size for the paired-samples t test, whereas r denotes the absolute effect size for the Wilcoxon signed-rank test. Differences were calculated as K_2EDTA minus Li-heparin.*

ICC(A,1) values calculated for K_2EDTA and Li-heparin measurements ranged from 0.218 to 0.998. Good or excellent agreement was observed for most leukocyte and erythrocyte parameters and hematological inflammatory indices. BAS, BAS%, and MCHC showed moderate agreement. Agreement levels were more variable for the platelet parameters. PLT showed good agreement, PCT showed moderate agreement, and MPV and PDW showed poor agreement. The ICC(A,1) values, 95% confidence intervals, and agreement levels for all parameters are presented in Table 2.

Table 2. Results of the intraclass correlation coefficient between K_2EDTA and Li-heparin measurements.

Parameter	ICC(A,1) (%95 GA)	Level of agreement
WBC	0.979 (0.939–0.993)	Excellent
NEU	0.992 (0.975–0.997)	Excellent
LYM	0.971 (0.902–0.990)	Excellent
MON	0.914 (0.765–0.970)	Excellent
EOS	0.956 (0.877–0.985)	Excellent
BAS	0.650 (0.239–0.866)	Moderate
NEU%	0.984 (0.954–0.995)	Excellent
LYM%	0.971 (0.917–0.990)	Excellent
MON%	0.754 (0.422–0.909)	Good
EOS%	0.883 (0.692–0.959)	Good
BAS%	0.611 (0.189–0.848)	Moderate
RBC	0.950 (0.576–0.988)	Excellent
HGB	0.943 (0.603–0.985)	Excellent
HCT	0.877 (0.312–0.967)	Good

Parameter	ICC(A,1) (%95 GA)	Level of agreement
MCV	0.998 (0.994–0.999)	Excellent
MCH	0.973 (0.890–0.992)	Excellent
MCHC	0.595 (0.137–0.843)	Moderate
RDW-CV	0.996 (0.985–0.999)	Excellent
RDW-SD	0.996 (0.986–0.999)	Excellent
PLT	0.799 (0.253–0.939)	Good
MPV	0.405 (−0.093–0.786)	Poor
PDW	0.218 (−0.112–0.598)	Poor
PCT	0.671 (−0.085–0.914)	Moderate
NLR	0.975 (0.928–0.991)	Excellent
MLR	0.781 (0.466–0.921)	Good
PLR	0.841 (0.332–0.954)	Good
SII	0.785 (0.318–0.931)	Good
SIRI	0.947 (0.851–0.982)	Excellent
AISI	0.943 (0.825–0.981)	Excellent

Note: *ICC(A,1) denotes the intraclass correlation coefficient based on a two-way mixed-effects model, absolute agreement, and a single-measure approach. CI denotes confidence interval. ICC values were classified as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), or excellent (>0.90) agreement. ICC estimates should be interpreted together with their confidence intervals.*

In the Bland-Altman analysis, with differences calculated as K_2EDTA minus Li-heparin, the mean bias for WBC was close to zero. Positive bias values for PLT, MPV, PCT, PLR, and SII indicated that measurements obtained from K_2EDTA samples were generally higher. In contrast, the negative bias observed for PDW was consistent with the lower values obtained from K_2EDTA samples. The mean bias and 95% limits of agreement for each parameter are presented in Table 3. Bland-Altman plots for WBC, PLR, PLT, MPV, PDW, and PCT are shown in Figure 1.

Table 3. Bland-Altman analysis of agreement between K_2EDTA and Li-heparin measurements.

Parameter	Bias	95% limits of agreement (lower–upper)
WBC	−0.1273	−0.8338–0.5792
NEU	−0.0293	−0.1964–0.1377
LYM	−0.1440	−0.6702–0.3822
MON	−0.0073	−0.1569–0.1422
EOS	−0.0020	−0.0268–0.0228
BAS	0.0007	−0.0044–0.0057
NEU%	0.0600	−2.2243–2.3443
LYM%	−0.3067	−3.7460–3.1327
MON%	0.3267	−2.2603–2.9136
EOS%	−0.0467	−0.6004–0.5070
BAS%	0.0133	−0.0556–0.0823
RBC	−0.1440	−0.4111–0.1231
HGB	−0.2067	−0.6222–0.2089

Parameter	Bias	95% limits of agreement (lower–upper)
HCT	−0.9067	−2.6321–0.8187
MCV	0.0400	−0.4932–0.5732
MCH	0.1933	−0.3779–0.7646
MCHC	3.2667	−7.2483–13.7817
RDW-CV	−0.1800	−0.7354–0.3754
RDW-SD	−0.4333	−1.9689–1.1022
PLT	106.5333	−126.6394–339.7061
MPV	0.5333	−0.0094–1.0760
PDW	−0.4733	−1.1083–0.1616
PCT	1.0593	−0.1124–2.2311
NLR	0.0092	−0.0501–0.0685
MLR	0.0034	−0.0399–0.0467
PLR	40.1682	−47.3470–127.6833
SII	49.6791	−76.4105–175.7688
SIRI	−0.0048	−0.0697–0.0600
AISI	12.0365	−35.5015–59.5745

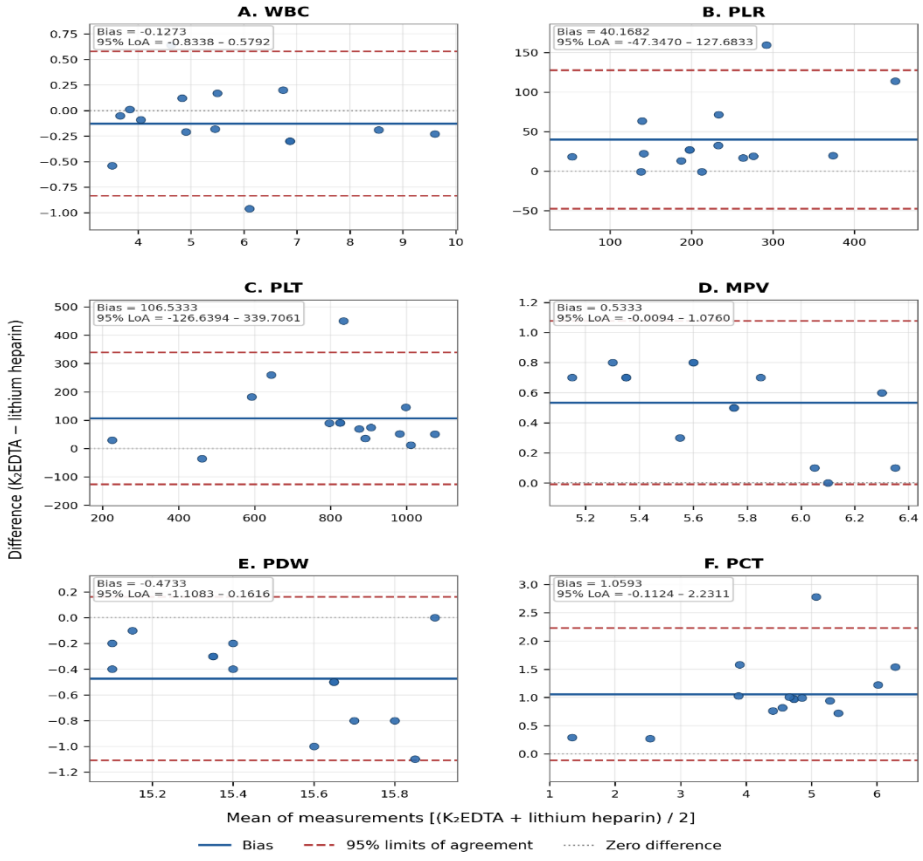


Figure 1. Bland-Altman plots comparing paired K_2EDTA and Li-heparin measurements for WBC, PLR, PLT, MPV, PDW, and PCT. The solid blue line represents the mean bias, the dashed red lines represent the 95% limits of agreement, and the dotted grey line represents zero difference.

DISCUSSION

In this study, routine hematological parameters and complete blood count-derived inflammatory indices were compared in paired blood samples collected into K_2EDTA and lithium heparin tubes from healthy female rats. The most significant differences were observed in platelet parameters. In samples with K_2EDTA, PLT, MPV, and PCT were higher, while PDW was lower. RBC, HGB, and HCT levels were higher in samples containing lithium heparin, while MCHC was higher in samples with K_2EDTA. There were no significant differences in most leukocyte parameters among the anticoagulants. However, the absolute LYM count was lower in samples in tubes containing K_2EDTA. Among the hematological inflammation indices, only the PLR and SII differed, and both indices were higher in samples containing K_2EDTA. These results suggest that anticoagulant-related differences in cell counts may also be apparent in the indices derived from these cells.

In the present study, the absolute counts of WBC, NEU, MON, EOS, and BAS, as well as the percentage values in the leukocyte differential count, were found to be similar in samples containing K_2EDTA and lithium heparin. Ali et al. (2020) also reported similar results regarding total and absolute leukocyte counts between samples treated with K_3EDTA and lithium heparin in rats, and observed significant differences primarily in samples treated with sodium citrate (Ali et al. 2020). Moorhead et al. (2016), however, while identifying a statistically significant difference in WBC counts between the two anticoagulants in paired rat samples, demonstrated that the mean values for the two anticoagulants were similar (Moorhead et al. 2016). Studies conducted on other animal species have reported inconsistent results regarding the effects of anticoagulants on leukocyte parameters. Bauer et al. (2012) found that lymphocyte and monocyte counts in cats were higher in samples containing K_3EDTA than in those containing lithium heparin; however, they did not detect a significant anticoagulant effect on the parameters examined in horses (Bauer et al. 2012). In the present study, however, only the absolute LYM count was found to be lower in samples containing K_2EDTA, while the LYM percentage remained similar between the two anticoagulants. This result could be interpreted within the context of the current study group and the analytical conditions used, without generalizing it to other species.

When erythrocyte parameters were evaluated, the RBC, HGB, and HCT parameters were found to be lower in samples containing K_2EDTA, while the MCV parameter was similar for both anticoagulants. These findings suggest that some erythrocyte results may vary depending on the type of anticoagulant used in our laboratory conditions. Ali et al. (2020) reported no significant differences in erythrocyte parameters between samples treated with K_3EDTA and Li-heparin in rats (Ali et al. 2020). Moorhead et al. (2016), on the other hand, observed similar RBC and HGB values in paired rat samples treated with both anticoagulants, but found HCT to be higher in EDTA-treated samples (Moorhead et al. 2016). In contrast, Vatn et al. (2000) reported that RBC, HGB, and HCT values in lamb blood were significantly higher in samples treated with Li-heparin than in those treated with K_3EDTA (Vatn, Framstad, and Torsteinbø 2000). They noted that the average differences between the two anticoagulants did not exceed 4% and were not clinically significant, and suggested that part of the difference might be related to the dilution created by liquid EDTA (Vatn et al. 2000). The variation in the direction and magnitude of results across studies indicates the potential influence of the type of sample, the form and amount of anticoagulant in the tube, the analytical system, and pre-analytical conditions on the results. In the present study, the fact that MCV remained unchanged and the absolute differences between RBC, HGB, and HCT were relatively small suggests that statistical significance does not necessarily indicate a clinically significant difference. Since MCHC is calculated using HGB and HCT, the fact that the proportional decrease in HCT was slightly greater than the decrease in HGB in samples containing K_2EDTA may have contributed to the higher MCHC values.

The most significant differences among anticoagulants were observed in platelet parameters. In samples collected with K_2EDTA, PLT, MPV, and PCT were higher, while PDW was lower, and large effect sizes were observed for these parameters. These findings may indicate that the anticoagulant used can cause significant differences in platelet test results. Moorhead et al. (2016) reported that, in paired rat samples, the mean PLT values of heparinized samples remained at approximately 58-73% of those of EDTA-treated samples at various dilution levels (Moorhead et al. 2016). In the same study, findings consistent with clustering were observed in the platelet graphs and histograms of the heparinized samples, whereas no similar findings were observed in the paired EDTA-treated samples (Moorhead et al. 2016).

A study on cats also demonstrated that exposure to heparin before samples were transferred to EDTA tubes, as well as the tube filling volume, could affect automated platelet results; however, other hematology parameters were mostly preserved (Norsworthy et al. 2021). It has previously been reported that heparin may be associated with platelet activation and aggregation (Banfi et al. 2007). Therefore, the platelet clumping reported by Moorhead et al. (2016) in heparinized rat samples provides a possible preanalytical explanation for the lower PLT levels observed in Li-heparin-treated samples in this study (Moorhead et al. 2016).

The fact that PLT differences are associated with changes in MPV and PDW suggests that the anticoagulant used may affect not only the platelet count but also results that indicate the platelet volume and size distribution. It has been reported that platelets exposed to EDTA can change from a discoid shape to a spherical shape over time, and that this change can lead to a noticeable increase in platelet volume, particularly in impedance-based analyses (Banfi et al. 2007). Since PCT is derived from platelet count and mean platelet volume, the fact that both PLT and MPV are higher in K_2EDTA samples is consistent with an increase in PCT. In a study comparing the experimental heparin-iloprost tube with EDTA in human blood, platelet counts differed when measured by the impedance method, while no significant difference was observed when measured by the fluorescence method; MPV, however, was measured to be approximately 5% lower in the heparin-iloprost tube (Radziwon-Balicka et al. 2022). These findings suggest that platelet results may vary not only depending on the anticoagulant used but also according to the measurement methods employed.

The hematological inflammation indices were found to be higher only in the PLR and SII samples containing K_2EDTA. The PLR and SII are both calculated based on platelet and lymphocyte values. Therefore, it is known that higher PLT and lower LYM values in K_2EDTA-treated samples contribute to an increase in these (Dugăeşescu et al. 2025; Erturk et al. 2026). The fact that NEU values remain similar between the two anticoagulants suggests that the difference in SII is primarily related to the PLT and LYM results. Conversely, the fact that NLR, MLR, and SIRI are similar indicates that the limited difference in LYM, combined with the unchanged NEU and MON values, does not result in a distinct divergence in these indices. Although PLT is included in the AISI formula, this index did not differ among anticoagulants. This finding indicates that changes in PLT are not reflected to the same extent in the multicomponent AISI values, which also include NEU and MON. Therefore, it can be concluded that the anticoagulant effect is not the same across all indices and may vary depending on the cellular components included in the index.

Inflammation indices derived from complete blood counts are being studied as readily available helpful indicators to aid in the diagnosis of various diseases, monitor disease activity, predict prognosis, and evaluate treatment response (Dugăeşescu et al. 2025). The interaction of platelets with leukocytes, their secretion of cytokines and chemokines, and their contribution to the regulation of the immune response support the biological significance of platelet-containing indices such as PLR and SII (Maouia et al. 2020; Sonmez and Sonmez 2017). The fact that reference ranges for these indices have been reported in healthy cats also emphasizes the increasing interest in their use in veterinary medicine and the importance of species-specific assessment (Erturk et al. 2026). However, since these indices alone may have limited ability to identify a specific disease or predict its prognosis, they must be interpreted in the context of clinical and experimental findings (Dugăeşescu et al. 2025; Islam et al. 2024). The fact that PLR and SII results differ in samples taken simultaneously from the same rats simply by altering the anticoagulant demonstrates that preanalytical conditions can influence index values even in the absence of any actual inflammatory response. For this reason, it is important to take into account the anticoagulant used when interpreting hematological inflammation indices and comparing them across different studies.

Validity tests and agreement analyses provide complementary information for evaluating differences between anticoagulants. Paired comparisons indicate whether there is a systematic difference between two anticoagulants, while the ICC(A,1) measures the absolute agreement of the measurements, and the Bland-Altman analysis reveals the direction of the difference and the dispersion of individual measurements (Bland and Altman 1986; Koo and Li 2016). The fact that high ICC values were obtained for some parameters in this study does not mean that there were no systematic differences related to the anticoagulant. This trend was particularly evident in the PLT, PLR, and SII, where good ICC values were accompanied by positive bias and wide confidence intervals.

The lower concordance observed in MPV, PDW, and PCT also supports the notion that platelet-related outcomes are more sensitive to changes in anticoagulation. These findings do not support the direct interchangeability of platelet parameters and platelet-based inflammation indices obtained from different anticoagulants and highlight the importance of standardizing the anticoagulant used.

The results of this study suggest that collecting blood samples in heparin- or EDTA-containing tubes may influence hematological parameters and that the choice of anticoagulant may therefore be an important consideration in data interpretation. When K_2EDTA is used for some measurements and lithium heparin for others, differences observed particularly in platelet parameters, PLR, and SII may be attributable to the anticoagulant used rather than to true biological variation. Therefore, the same anticoagulant should be used across all animals and sampling time points, and the type of collection tube should be clearly reported in the Methods section. Given that K_2EDTA is recommended as the standard anticoagulant in mammalian hematology, its use for routine complete blood count measurements may help maintain comparability across studies (England et al. 1993; Moorhead et al. 2016; Vap et al. 2012).

This study has several limitations. Although the sample size was determined based on a power analysis for paired comparisons, the inclusion of 15 rats limited the precision of the ICC confidence intervals and Bland-Altman limits of agreement. Because the study was conducted exclusively in healthy female Wistar Albino rats using a single hematology analyzer, with samples analyzed immediately after collection, the generalizability of the findings to different sexes, ages, strains, and disease models, as well as to different analytical systems and storage conditions, is limited. The absence of a systematic assessment of platelet aggregation in peripheral blood smears did not allow direct investigation of the possible mechanism underlying the lower PLT values observed in lithium heparin samples. In addition, because multiple hematological parameters were tested separately without adjustment for multiple comparisons, findings at the $p < 0.05$ level should be interpreted with caution. Nevertheless, the paired design, in which each rat served as its own control, the alternating order of tube filling, the standardization of sample volumes, and the support of difference testing with effect-size and agreement analyses represent important strengths of the study.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, a comparison of paired blood samples collected from the same healthy female rats using K_2EDTA and lithium heparin revealed that the differences between the anticoagulants were most pronounced in platelet parameters. While most leukocyte parameters remained similar, limited differences were observed in some erythrocyte parameters, and all platelet parameters varied depending on the anticoagulant used. The finding that PLT, MPV, and PCT were higher and PDW was lower in K_2EDTA-treated samples, accompanied by increases in PLR and SII, demonstrated that preanalytical changes in baseline cell counts can also be reflected in inflammation indices derived from the complete blood count. Although agreement analyses revealed good ICC values for some parameters, they also showed that systematic bias may persist and that direct comparison of results related to platelets between the two anticoagulants may not be appropriate.

In studies evaluating complete blood count parameters and hematological inflammatory indices in rats, using the same anticoagulant throughout the sampling and measurement procedures and clearly specifying the type of anticoagulant may be important for the interpretability of the results. In accordance with standard practices in mammalian hematology, the use of K_2EDTA may contribute to the reliability of results and help maintain comparability across studies. When Li-heparin is used, platelet parameters, PLR, and SII can be interpreted more appropriately by taking into account the potential preanalytical effect of the anticoagulant. Future studies involving larger groups of rats with varying sex, age, and pathophysiological characteristics, and evaluating analysis times using different analyzers, could further clarify the extent and applicability of these findings by incorporating microscopic evaluation of platelet aggregation and alternative platelet counting methods.

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EVALUATION OF SOME FEED ADDITIVES USED IN CAT-DOG NUTRITION FROM THE PERSPECTIVE OF ANIMAL HUSBANDRY

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Abstract
Balanced and adequate nutrition for cats and dogs is crucial not only for meeting basic nutrient requirements but also for supporting gastrointestinal health, immune function, and overall quality of life. In recent years, there has been a significant shift in pet nutrition from diets that merely meet energy and nutrient needs to nutritional approaches aimed at supporting the animal's physiological functions. In this context, probiotics, prebiotics, functional fibers, postbiotics, omega-3 fatty acids, antioxidants, and various plant-based bioactive compounds are among the key functional feed additives considered for use in cat and dog foods. A better understanding of the relationship between the gut microbiota and the host animal has particularly heightened scientific interest in the use of these additives. Consequently, the use of feed additives is significant not only for supporting gastrointestinal and metabolic health but also for enhancing nutrient utilization, maintaining optimal body condition, and supporting physiological performance throughout the animal's life. The fact that probiotics contribute beneficial microorganisms to the gut ecosystem, prebiotics support the growth of specific microorganisms, and postbiotics exert effects through beneficial microbial derived components without containing live microorganisms demonstrates that these additives operate via distinct mechanisms. However, it must be noted that the efficacy of these additives can vary depending on the product's formulation, dosage, the animal's age and health status, and the composition of the existing diet.
Keywords: cat and dog nutrition, feed additives, probiotic, prebiotic, postbiotic.

İntroduction

Cats and dogs are pets that have held an important place in people's lives for many years. It is reported that interactions with these animals can positively contribute to the mental health and general well-being of children, adolescents, and adults, and that cat and dog ownership has become increasingly common in many countries in recent years (Li & Wu, 2023). Compared to the past, the approach to pet nutrition has evolved beyond merely providing the nutrients necessary for survival into a more comprehensive responsibility aimed at safeguarding the animals' health, well-being, and quality of life. In this context, it is becoming increasingly important for pet owners to regularly monitor their animals' nutritional status and health. On the other hand, studies examining the effects of pet ownership on humans report that interactions with cats and dogs can provide various psychological benefits (El-Alayli et al., 2006). These benefits include higher self-esteem, a more positive mood and life satisfaction, and lower feelings of loneliness among pet owners (Şimşek, 2024).

Providing an adequate and balanced nutritional program tailored to their specific needs is of great importance for cats and dogs to lead healthy lives. The primary objective in the nutrition of these animals is to meet their energy and nutrient requirements in accordance with their species, age, physiological status, and activity level (Yıldırım and Şen, 2024). With a better understanding of the effects of nutrition on health, it is recognized that pet foods are not merely carriers of nutrients, but also sources of functional components capable of influencing the gastrointestinal system, the immune system, and metabolic processes (NRC, 2006; Freeman et al., 2011).

Elucidating the role of the microbial community—particularly that within the gastrointestinal tract—in animal health has contributed to the emergence of new areas of research in companion animal nutrition. The gut microbiota plays a role in numerous processes, such as nutrient metabolism, the production of short-chain fatty acids, the maintenance of the intestinal barrier, and the regulation of immune responses

(Pilla & Suchodolski, 2019). Consequently, the use of functional feed additives aimed at supporting the microbiota and the gastrointestinal system in cat and dog foods has gained importance in recent years (Batı et al., 2023).

Additives are incorporated into processed pet diets to ensure nutritional benefits and food safety, and to maintain desired characteristics such as color, taste, texture, stability, and resistance to spoilage (Craig, 2021).

The functional nutrition approach aims to support specific physiological functions, going beyond merely meeting the animal's basic nutrient requirements. Additives used within this approach include probiotics, prebiotics, functional fibers, postbiotics, omega-3 fatty acids, antioxidants, and bioactive compounds of plant origin.

Although each of these components can exert effects through different biological mechanisms, gastrointestinal system health constitutes one of the key areas of research in functional pet nutrition (Sarı and Sarıışık, 2026).

Due to the differences in the nutritional physiology of cats and dogs, species-specific differences must be taken into account when evaluating functional additives. In particular, owing to their nature as obligate carnivores, cats have metabolic requirements for certain nutrients that differ from those of dogs (NRC, 2006).

The aim of this study is to evaluate certain functional feed additives used in cat and dog nutrition; in terms of their mechanisms of action, intended uses, and potential contributions to animal husbandry, in light of current literature.

Probiotics

Just like in humans, the health and well-being of pets depend on their gut microbiota. Providing appropriate care and a balanced diet is crucial for maintaining the health and well-being of dogs and cats. However, since variations in microbiota can increase susceptibility to pathogens and harmful environmental factors, it is of great importance to seek new tools to protect dogs, cats, and their owners against pathogens. Specific probiotic strains and defined combinations thereof can be beneficial in the nutrition, care, and treatment of dogs and cats (Batı et al. 2023).

Probiotics are defined as live microorganisms that confer health benefits to the host when administered in adequate amounts (Hill et al., 2014).

Today, probiotic additives are recognized as growth-promoting agents, particularly in animals, and their efficacy is supported by studies demonstrating their role in enhancing disease resistance. Probiotics prevent the disruption of physiological balance in animals and promote the development of a healthy, natural microflora. It has also been demonstrated that probiotics increase enzyme activity within the gastrointestinal tract and improve the digestibility of ingested food (Sharma et al., 2018). The majority of probiotics studied in the context of companion animal health belong to the genera *Lactobacillus*, *Bifidobacterium*, and *Enterococcus* (Wernimont et al., 2020).

One of the primary purposes of using probiotics in cats and dogs is to support intestinal microbial balance.In addition, they have potential effects such as maintaining intestinal barrier function and modulating the immune system (Grześkowiak et al., 2015; Ural et al., 2025).

In a study involving sled dogs prone to exercise-induced diarrhea, supplementing the diet with a probiotic containing *Enterococcus faecium* F68, *Bacillus coagulans*, *Lactobacillus acidophilus*, and other agents shortened the recovery time from diarrhea and improved fecal scores (Jugan et al., 2017). Positive effects of probiotics have been observed in cats and dogs with intestinal disorders. Oral administration of products fermented with *Bacillus licheniformis* alleviated symptoms in cases of chronic diarrhea and reduced fecal *Clostridium perfringens* levels (Yang and Wu, 2023). Furthermore, including the *Enterococcus faecium* SF68 strain in the diet of cats undergoing amoxicillin-clavulanate treatment improved fecal quality (Torres-Henderson et al., 2017).

Furthermore, it should be noted that the effects of probiotics may be specific to the microbial strain. It is reported that different strains within the same species can yield different outcomes regarding colonization of the gastrointestinal tract, metabolite production, and interaction with the immune system (Erkmen, 2026).

This situation necessitates that the use of probiotics in pet foods be addressed by evaluating not only the microorganism species but also the strain, viability, dosage, food matrix, and storage conditions in conjunction.

Prebiotics

Prebiotics are considered substrates that are selectively utilized by microorganisms conferring health benefits to the host. By supporting a healthy gut microbiome, they aid in improved nutrient absorption in cats and dogs, reduce inflammation, and boost immunity (Kumar et al ., 2023).

Prebiotics are a group of compounds that include dietary fibers, starches, non-absorbable sugars, sugar alcohols, and oligosaccharides. Fermentable carbohydrates and certain functional fiber sources, in particular, can influence the metabolic activity of the gut microbiota (Çetin & Bal, 2025). The production of short-chain fatty acids; such as acetate, propionate, and butyrate, resulting from the microbial fermentation of fermentable fibers in the gut is significant for gut physiology. These metabolites can contribute to the energy metabolism of intestinal epithelial cells and play a role in regulating the intestinal environment (Pilla & Suchodolski, 2019).

Overall, it has been concluded that small amounts of prebiotics exert beneficial effects on various parameters of digestive health (Kanakupt et al ., 2011).

Prebiotics are becoming increasingly popular in animal feeds particularly for young pigs, poultry, and domestic cats and dogs to improve gut health and treat health issues (Fatıma and Bayram, 2024). Studies conducted on dogs and cats have shown that prebiotics support gut health, exert an immunomodulatory effect, and improve fecal characteristics (Félix et al ., 2009). Examples of oligosaccharides used as prebiotics include galactooligosaccharides, lactooligosaccharides, xylooligosaccharides, fructooligosaccharides, soy oligosaccharides, and mannan-oligosaccharides. Measuring the effects of prebiotics in dogs and cats is challenging, as they are significantly influenced by individual factors and diet. For instance, diets containing animal by-products lead to higher levels of fermentable nitrogen in the colon and the formation of putrefactive compounds such as ammonia and biogenic ammonium compounds. Conversely, plant-based protein sources like soybeans contain fermentable polysaccharides and oligosaccharides; they produce less undigested nitrogen in the large intestine and exhibit effects similar to those of prebiotics (Félix et al ., 2013a). Therefore, the interaction between dietary components and prebiotics requires further investigation (Félix et al ., 2013b).

Postbiotics: Next-Generation Functional Additives

One of the notable approaches in pet nutrition in recent years is the use of postbiotics. The International Scientific Association for Probiotics and Prebiotics (ISAPP) defines postbiotics as preparations comprising inanimate microorganisms and/or their components that confer a health benefit on the host (Salminen et al., 2021). Postbiotics are considered a reliable alternative due to their unique chemical structures, safety profiles, lack of established toxicity, longer shelf life compared to probiotics, resistance to intestinal enzymes, stability within the gastrointestinal tract, and the presence of various signaling molecules capable of exerting anti-inflammatory, immunomodulatory, anti-obesogenic, antihypertensive, hypocholesterolemic, antiproliferative, and antioxidant activities. Postbiotics can be utilized in functional foods and the pharmaceutical industry for disease prevention and therapeutic purposes. Postbiotics, which positively influence health, can be regarded as a safer alternative to live probiotics (Gökırmaklı et al., 2021). Since they are not live microorganisms, postbiotics exert beneficial health effects while minimizing risks associated with their administration. Therefore, an advantage of postbiotics is that they demonstrate efficacy in the body similar to prebiotics or probiotics but with fewer side effects (Żółkiewicz et al ., 2020).

Postbiotic preparations may contain various biological components such as microbial cell constituents, cell wall structures, enzymes, peptides, and diverse metabolites. The potential effects of these components on the intestinal barrier, immune response, and microbial balance are currently being investigated (Żółkiewicz et al ., 2020; Salminen et al ., 2021).

Gastrointestinal diseases are frequently observed in dogs and cats, and the onset of these conditions is closely linked to the gut microbiota. Previous studies have demonstrated that feeding healthy domestic cats inactivated Bifidobacterium animalis subsp . lactis improved coat condition, enhanced intestinal barrier integrity, and reduced levels of permeability markers such as diamine oxidase and lipopolysaccharide (Wang et al ., 2025).

Studies have evaluated the effects of postbiotic supplements (inactivated bacteria and partial yeast fractions) on digestive symptoms in healthy cats experiencing mild digestive imbalances, such as loose stools, increased fecal output, and flatulence. The results indicated that the tested supplements were beneficial in supporting digestive health in cats suffering from mild gastrointestinal disorders (Nicolas et al ., 2026).

A study supports the use of postbiotics as a safe and effective nutritional approach to improve and maintain gastrointestinal and immune health in cats. Lin et al. (2019) administered a dried product derived from *Saccharomyces cerevisiae fermentation* (SCFP) to healthy adult dogs. SCFP slightly modulated the composition and activity of the fecal microbiota by increasing *Bifidobacterium*, decreasing Clostridium, and reducing phenol and indole concentrations; thus, it demonstrated that SCFP could be used in dog food to improve gut health by positively modulating the gut microbiota, enhancing immune function, and reducing inflammation.

The anti-inflammatory effects of postbiotics are crucial for the health of dogs and cats. They serve as a fundamental nutritional strategy for controlling chronic inflammation, protecting the intestinal barrier, supporting immune balance, and alleviating age-related diseases and allergies; furthermore, they are more stable, safe, and effective than traditional probiotics. In a study conducted by Sun et al. (2025), cats were divided into two groups. The control group received only yogurt, while the experimental group was given yogurt supplemented with 2% postbiotics. The study results revealed that, compared to the control group, the combination treatment of yogurt and 2% postbiotics significantly reduced levels of total bilirubin, total bile acids, triglycerides, glucose, blood urea nitrogen, creatinine, tumor necrosis factor-α (TNF-α), and interleukin-6 (IL-6) in cats ($p<0.05$).

It was reported that postbiotics can work synergistically with yogurt to effectively mitigate inflammatory responses in the body (Sun et al., 2025).

Dental diseases are common in the routine care of dogs and cats; periodontal disease and halitosis are the most prevalent conditions. Specific pathogenic bacteria in the oral cavity can produce volatile sulfur compounds (VSCs), which cause halitosis and are closely associated with poor oral health. Sordillo et al. (2025) conducted a randomized clinical trial to evaluate the ability of Superculture Pet Oral a novel canine oral health postbiotic (COHP) to reduce bad breath in dogs. The study demonstrated that COHP could reduce the compounds responsible for canine halitosis. Throughout the study, COHP significantly reduced VSCs by 27% and was shown to significantly alleviate halitosis after just seven days of treatment.

Immune function serves as a fundamental defense mechanism against pathogen invasion and a means of maintaining homeostasis in dogs and cats; its proper functioning directly determines the pet's health status and susceptibility to disease. Santoro Domenico et al. [2021] reported that the daily use of a novel postbiotic spray containing heat-treated (HT) *Lactiplantibacillus plantarum* CECT 9161 significantly alleviated the clinical symptoms of mild-to-moderate atopic dermatitis in dogs. In the context of pet food, postbiotics are considered a promising area of research, particularly regarding the development of functional foods, the support of gut health, and the enhancement of product stability. However, it should be noted that the effects of postbiotics may vary depending on the microorganism used, the inactivation method, production conditions, and the active ingredients present in the preparation. Therefore, comparing different postbiotic preparations in dogs and cats through controlled studies is of importance (Zhang et al., 2026).

Omega-3 Fatty Acids

In animals, omega-3 serves as a precursor metabolite for the production of fatty acids. Omega-3 polyunsaturated fatty acids specifically eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are considered functional lipids in pet nutrition. These fatty acids are known to play a role in the regulation of inflammatory processes and in cellular membrane functions (Bauer, 2011). Omega-3 fatty acids (EPA and DHA), which are abundant in fish oils, are used in cat and dog foods to support skin and coat health, regulate inflammatory processes, and provide nutritional support in certain clinical conditions (Vendramini et al., 2025).

Omega-3 fatty acids particularly EPA and DHA are key components of cardiac nutrition due to their anti-inflammatory, anti-arrhythmic, and metabolic regulatory effects. Clinical studies have shown that omega-3 supplementation can extend lifespan and improve the quality of life for patients (Freeman et

al., 1998; Woldemeskel, 2019; Vendramini et al., 2025). However, since omega-3 fatty acids are susceptible to oxidation, careful consideration must be given to food formulation and storage conditions. Therefore, their use in combination with antioxidants is significant in the context of functional pet food technology.

Plant Extracts and Bioactive Products.

Plant-derived extracts, phenolic compounds and other bioactive ingredients are among the functional ingredients that are being examined for use in pet foods. Antioxidant and antimicrobial properties of these substances make them attractive as alternatives for other functional ingredients. There is a growing trend for natural alternatives (such as growth promoters, immunostimulants and antioxidative agents) instead of antibiotics.

Phytomedicinals (plants) are used for both health benefits and for disease treatment. Plant extracts are preferred as they are low toxicity and have low residue profiles. Medicinal herbs and their extracts are used in animal nutrition (Paray et al. 2021). Pets (dogs and cats) are very much an integral part of families today, and their diet is key. Plant extracts like polyphenols and enzymes are found in pet foods for their health benefits (metabolism and gut health).

Pet owners are adding supplements like tea polyphenols, quercetin, curcumin to their pets' diets. These natural extracts can prolong the shelf life and quality of pet food by replacing toxic synthetic antioxidants. Medicinal plants have therapeutic benefits and can reduce disease resistance, and in turn, help prevent disease as well. But it is essential that these extracts are safe and properly metabolized by the pets (Guo et al., 2024). But for pets, further research is needed (Yanar and Aktaş, 2021).

The health of pets can be seen in more macro-level ways in terms of weight, skin and coat, and metabolism. Campigotto et al. (2020) did a study on curcumin in dog food and found no difference in weight gain between dogs fed diets with and without curcumin. Similarly, no differences were found at any point in the diet for Beagle dogs to be fed synthetic antioxidants and vitamin E mixed with essential oils (clove, rosemary and thyme), but body weight decreased over time in both groups (Schlieck et al., 2021).

Rees et al. (2001) investigated the effect of FLX and sunflower seed (SUN) on skin and coat quality in 18 dogs over a one month period. In both groups, the coat quality was improved for a short period of time, but this effect was not sustained for longer than 28 days. The skin condition scores improved significantly around day 14 and the authors found that supplementing with FLX or SUN in a short term in dogs, and therefore increasing the concentration of 18-carbon PUFAs in the skin and coat of the dog, is a good approach. In another study the effects of black ginseng (BG) on Beagle dogs were studied and serum samples were analysed by high-resolution magic-angle spinning (HR-MAS) nuclear magnetic resonance (NMR) spectroscopy. The dogs were treated with BG tablets for eight weeks and blood samples were taken at weeks 0, 4 and 8. Metabolic profiles showed an increase in glucose, BCAAs (isoleucine, leucine, and valine), alanine, glutamine, and histidine, and decrease in lactic acid and formate, indicating that BG enhances immunity and energy metabolism, confirming its biological utility and potential for pet health care (Yoon et al. 2020; Guo et al., 2024).

Conclusion and Recommendations

Fosterative feed additives play a crucial role in cat and dog nutrition, which are a key player in animal nutritional treatment beyond the traditional nutrition approach.

Probiotics, prebiotics, functional fibers, postbiotics, omega-3 fatty acids and plant-based bioactive compounds can also have a significant effect on gut microbiota in animal health and the gastrointestinal system and overall health of the animal. Functional additives are being studied in functional feed additives to assist animal health in cat and dog nutrition. Results of functional additives are quite different according to the source of the additive, dosage, animal species and their diet composition.

Future cat and dog nutrition can be considered to use functional feed additives as a more personalized system. The age of the animal, breed, physiological status, existing medical conditions, and gut microbiota profile will be important in designing functional diets. With the move from probiotics to postbiotics, there seem to be new research opportunities in terms of the stability of live microorganisms and product safety. Also, the effects of functional ingredients in combination is important to identify.

Therefore it is crucial that future research can be done not in the isolation of the effects of individual functional ingredients, but rather in the context of all aspects such as microbiota, metabolites, intestinal barrier, immune system, and the animal's clinical indicators.

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SİVAS İLİ KURU TARIM ALANLARI ÜRÜN DESENİNİN GENEL DEĞERLENDİRMESİ

GENERAL ASSESSMENT OF THE CROPPING PATTERN IN DRY FARMING AREAS OF SIVAS (TÜRKİYE)

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Özet
Sivas (Türkiye), karasal iklim koşulları ve sınırlı yağışın etkisi altında geniş alanlarda tarla bitkileri üretiminin yapıldığı önemli üretim merkezlerinden biridir. Bu çalışmada, 2020-2024 döneminde Sivas ilinde kuru tarım koşullarında yetiştirilen buğday, arpa, yulaf, çavdar, nohut, yeşil mercimek, kırmızı mercimek ve korunganın ekiliş alanı, üretim miktarı ve verim değerlerindeki değişimlerin değerlendirilmesi amaçlanmıştır. İncelenen dönemde buğday ve arpanın geniş ekiliş alanlarıyla ürün deseninin temelini oluşturduğu, ancak özellikle 2021 yılında kuraklık ve yetersiz yağışın her iki üründe de üretim ve verim değerlerini belirgin biçimde düşürdüğü görülmüştür. Buğday ve arpa üretimi 2021 ve 2024 yıllarında sırasıyla 391.692 ve 204.746 ton olarak gerçekleşirken 2024 yılında 658.284 ve 339.970 tona yükselmiştir. Yulaf, dönem içinde en dikkat çekici gelişmeyi gösteren tahıl olmuş ve ekiliş alanı 138.412 dekardan 252.712 dekara, üretim miktarı 39.653 tondan 74.004 tona yükselirken Sivas'ın Türkiye yulaf üretimindeki payı %12,61'den %18,98'e çıkmıştır. Çavdar üretimi daha sınırlı düzeyde kalmakla birlikte, kuraklık ve soğuk koşullara uyumu nedeniyle ürün çeşitliliği açısından önemini korumuştur. Baklagiller içerisinde nohut ekiliş alanı 73.884 dekardan 96.272 dekara, üretim miktarı ise 6.489 tondan 10.620 tona yükselmiştir. Yeşil mercimek üretimi yıllar arasında dalgalı bir seyir gösterirken, kırmızı mercimekte ekiliş alanı 1.282 dekardan 308 dekara ve üretim miktarı 140 tondan 34 tona gerilemiştir. Kuraklığa dayanıklı bir yem bitkisi olan korungada ekiliş alanı ve üretim miktarı azalmasına rağmen Sivas'ın Türkiye üretimindeki göreli payı korunmuştur. Sonuç olarak, 2020–2024 verileri Sivas'ta kuru tarım ürünlerinin üretim performansının yıllara göre önemli ölçüde değişebildiğini ve özellikle kuraklık ile yağış koşullarının verim üzerinde belirleyici olduğunu göstermektedir. Bu nedenle kuru koşullara uyum sağlayabilen tahıl, baklagil ve yem bitkilerinin ürün planlamasında verim, üretim istikrarı ve bölgesel uyum dikkate alınarak değerlendirilmesi önem taşımaktadır.
Anahtar kelimeler: Tahıllar, baklagiller, korunga, kuraklık, ürün deseni

Abstract
Sivas (Türkiye) is one of the important production centers where field crop production is carried out over extensive areas under the influence of continental climatic conditions and limited precipitation. This study aimed to evaluate the changes in cultivated area, production quantity, and yield values of wheat, barley, oats, rye, chickpea, green lentil, red lentil, and sainfoin grown under dry farming conditions in Sivas Province during the 2020-2024 period. During the examined period, wheat and barley constituted the basis of the cropping pattern with their extensive cultivation areas; however, particularly in 2021, drought and insufficient precipitation were observed to markedly reduce the production and yield values of both crops. Wheat and barley production in 2021 and 2024 amounted to

391,692 and 204,746 tons, respectively, while in 2024 they increased to 658,284 and 339,970 tons. Oats became the cereal showing the most remarkable development during the period, and its cultivated area increased from 138,412 decares to 252,712 decares, while its production quantity increased from 39,653 tons to 74,004 tons, and the share of Sivas in Türkiye's oat production rose from 12.61% to 18.98%. Although rye production remained at a more limited level, it maintained its importance in terms of crop diversity due to its adaptation to drought and cold conditions. Among pulses, chickpea cultivation area increased from 73,884 decares to 96,272 decares, while its production quantity increased from 6,489 tons to 10,620 tons. While green lentil production showed a fluctuating course among years, in red lentil, the cultivated area decreased from 1,282 decares to 308 decares and the production quantity decreased from 140 tons to 34 tons. Although the cultivated area and production quantity of sainfoin, a drought-tolerant forage crop, decreased, the relative share of Sivas in Türkiye's production was maintained. In conclusion, the 2020-2024 data show that the production performance of dry farming crops in Sivas may vary considerably from year to year and that especially drought and precipitation conditions are decisive on yield. Therefore, it is important to evaluate cereals, pulses, and forage crops that can adapt to dry conditions in production planning by taking yield, production stability, and regional adaptation into consideration.
Keywords: Cereals, pulses, sainfoin, drought, cropping pattern

GİRİŞ

Tarımsal üretimin sürdürülebilirliği; iklim özellikleri, toprak koşulları, su kaynaklarının kullanılabilirliği, yetiştirilen ürünlerin çevresel koşullara uyumu ve uygulanan üretim teknikleriyle yakından ilişkilidir. Özellikle yağışa dayalı üretim sistemlerinde bitkisel üretimin temel su kaynağını doğal yağışların oluşturması, üretim miktarı ve verimin yıllar arasında daha değişken bir yapı göstermesine neden olabilmektedir. Kurak ve yarı kurak alanlarda yalnızca toplam yağış miktarı değil, yağışın yetişme dönemi içerisindeki dağılımı ve bitkinin kritik gelişme dönemleriyle örtüşmesi de üretim performansı açısından önem taşımaktadır. Bu nedenle kuru tarım sistemlerinde mevcut toprak suyunun etkin kullanılması, bölgesel koşullara uyum sağlayabilen tür ve çeşitlerin yetiştirilmesi ve ürün deseninin çevresel sınırlılıklar dikkate alınarak oluşturulması önemlidir (Van Duivenbooden vd., 2000; Kutlu, 2010).

Bu çevresel kısıtlar altında, kuraklık stresine uyum sağlayabilen ve sınırlı su kaynaklarının etkin kullanımına olanak sağlayan özelliklere sahip serin iklim tahılları ve baklagiller, kuru tarım sistemlerinin önemli ürün grupları arasında yer almaktadır (van Duivenbooden vd., 2000; Dwivedi vd., 2018; Yu vd., 2021). Bununla beraber kuraklığın tahıl ve baklagil üretimi üzerindeki etkisinin ürün türüne ve yetişme koşullarına göre değişebildiği de farklı çalışmalarla ortaya konulmuştur (Daryanto vd., 2017). Kuru tarım alanlarının ürün deseninde tahıllar belirgin bir yere sahiptir. Buğday, dünya gıda güvenliği açısından temel ürünlerden biri olup küresel ölçekte beslenmede alınan enerji ve proteinin önemli bir bölümünü karşılamaktadır (Shiferaw vd., 2013). Türkiye'de de buğday üretimi, insan beslenmesindeki temel işlevinin yanında un ve unlu mamuller sanayisi açısından taşıdığı önem nedeniyle tarımsal üretimin başlıca unsurlarındandır (Aydın, 2022). Arpa ise insan beslenmesi ve sanayideki kullanımının yanı sıra özellikle hayvan beslenmesindeki rolüyle öne çıkmakta; farklı çevre koşullarına uyum yeteneği ve su kısıtına görece dayanıklılığı nedeniyle kuru tarım sistemlerinde önem kazanmaktadır (Elakhdar vd., 2022). Türkiye'de arpanın özellikle yem sektörü ve hayvancılıkla olan ilişkisi, ürünün tarımsal üretim sistemi içerisindeki önemini güçlendirmektedir (Kızılcan ve Altuntaş, 2025). Buğday ve arpanın yanında yulaf ve çavdar gibi diğer serin iklim tahılları da ürün çeşitliliğinin sağlanması ve farklı kullanım alanları bakımından önem taşımaktadır. Yulaf; hayvan yemi olarak kullanımının yanı sıra yüksek besin değeri, lif içeriği ve insan beslenmesinde giderek genişleyen kullanım alanlarıyla dikkat çeken bir tahıldır (Karaman vd., 2020). Çavdar ise hem tane hem de yem amacıyla değerlendirilebilmekte ve özellikle soğuk, kurak ve düşük verimli toprak koşullarına gösterdiği tolerans nedeniyle diğer bazı tahılların üretiminin sınırlandığı koşullarda alternatif oluşturabilmektedir (Newell ve Butler, 2013).

Bu özellikler, kuru tarım ürün deseninde yalnızca geniş alanlarda yetiştirilen temel tahılların değil, daha sınırlı üretim hacmine sahip türlerin de değerlendirilmesini gerekli kılmaktadır. Yemeklik tane baklagiller de kuru tarım sistemlerinin önemli bileşenleri arasında yer almaktadır. Nohut ve mercimek, insan beslenmesinde protein, karbonhidrat, lif, vitamin ve mineral kaynağı olmalarının yanında tarımsal üretim sistemi içerisinde baklagil özellikleri nedeniyle önem taşımaktadır. Türkiye'de yemeklik tane

baklagiller tahıllardan sonra önemli tarla bitkileri arasında yer almakta; nohut ile yeşil ve kırmızı mercimek başlıca üretimi yapılan türler arasında bulunmaktadır (Burhan ve Yılmaz Soydan, 2023). Nohut özellikle kurak ve yarı kurak alanlarda yetiştirilen önemli bir baklagil olmakla birlikte, su yetersizliği, üretim ve verimini sınırlayan temel çevresel faktörlerden biridir (Karkee vd., 2026). Mercimek de yarı kurak ve marjinal (verimsiz, eğimli, taşlı veya su kısıtı olan topraklarda) alanlarda yetiştirilebilmesi ve beslenme açısından protein, demir, çinko ve diğer besin bileşenlerini sağlaması nedeniyle gıda ve beslenme güvenliği açısından önemli bir üründür (Zeroual vd., 2023). Kuru koşullarda yetiştirilebilen yem baklagilleri, bitkisel üretim ile hayvancılık arasındaki ilişkinin sürdürülebilmesi açısından ayrıca önem taşımaktadır. Bu grupta yer alan korunga, derin kök sistemi sayesinde düşük yağış koşullarına uyum gösterebilen, ruminant beslemede değerlendirilen ve çeşitli agronomik ve çevresel özelliklere sahip çok yıllık bir yem bitkisidir (Mora-Ortiz ve Smith, 2018). Türkiye'de korunganın kaliteli kaba yem kaynağı olarak kullanılabilirliği üzerinde durulmakta; Sivas'ta da korunga üretiminin hayvancılıkla ilişkili yem bitkileri sistemi içerisinde yer aldığı görülmektedir. Nitekim Sivas'ta yem bitkileri üretimi üzerine yapılan çalışmalar yonca ve korunganın bölgedeki üreticiler açısından önemli yem bitkileri arasında bulunduğunu göstermiş, Sivas'tan elde edilen yerel korunga materyalleri de besleme özellikleri açısından araştırılmıştır (Altıntaş vd., 2017; Ülger ve Kaplan, 2016). Sivas'ın karasal iklim yapısı ve geniş tarım alanları, ilde tarla bitkileri üretiminin önemli ölçüde yağış koşullarıyla ilişkili olarak yürütülmesine neden olmaktadır. Sivas'ta buğday ve arpa üretiminin su ayak izinin değerlendirildiği bir çalışmada, 2020 yılı için her iki üründe de mavi su ayak izinin sıfır hesaplanması, bu ürünlerin üretiminde yağış suyunun taşıdığı önemi göstermektedir (Polat Bulut ve Topal Canbaz, 2022). Bu koşullar altında farklı tahıl, baklagil ve yem bitkilerinin yıllar içerisindeki üretim performanslarının birlikte değerlendirilmesi, ilin kuru tarım ürün desenindeki değişimin ortaya konulması bakımından önemlidir. Bu çalışmada Sivas ilinde kuru tarım koşullarında yetiştirilen buğday, arpa, yulaf, çavdar, nohut, yeşil mercimek, kırmızı mercimek ve korunganın 2020-2024 dönemindeki ekiliş alanı, üretim miktarı ve verim değerlerindeki değişimlerin değerlendirilmesi amaçlanmıştır.

SİVAS İLİNDE KURU TARIMDA YETİŞTİRİLEN TAHIL ÜRÜNLERİ

Buğday (*Triticum aestivum* L.) Üretimi

Buğday, insan beslenmesinin temel tahıl ürünlerinden biri olup dünya gıda güvenliği açısından stratejik bir öneme sahiptir. Küresel ölçekte günlük enerji ve protein alımına önemli katkı sağlaması, ürünün yalnızca tarımsal değil aynı zamanda sosyoekonomik açıdan da önemini artırmaktadır (Shiferaw vd., 2013). Türkiye'de de temel gıda ürünlerinin başında gelen buğday, üretim miktarı, tüketim düzeyi ve tarıma dayalı sanayilerle ilişkisi bakımından önemli bir tarla bitkisidir (Aydın, 2022). Sivas'ta buğday üretimi geniş alanlarda gerçekleştirilmekte olup ilin yağışa dayalı tarımsal üretim yapısının temel bileşenlerinden birini oluşturmaktadır. Sivas'ta buğdayın su ayak izi üzerine yapılan değerlendirmeler de yağış suyunun üretimdeki belirleyici rolüne işaret etmektedir (Polat Bulut ve Topal Canbaz, 2022). Bu özellikler, Sivas'ta buğday üretiminin yalnızca ekiliş alanı bakımından değil, üretim ve verimdeki yıllar arası değişimlerle birlikte değerlendirilmesini gerekli kılmaktadır.

Bu doğrultuda 2020-2024 dönemi incelendiğinde, Sivas'ta buğday ekiliş alanının beş yıllık dönem boyunca büyük ölçüde korunduğu ve özellikle 2023-2024 döneminde arttığı görülmektedir. Buna karşın üretim miktarındaki değişim ekiliş alanına göre daha belirgin olmuş; 2021 yılında üretim 391.692 tona kadar gerilerken 2024 yılında 658.284 tona ulaşmıştır. Benzer değişim verim değerlerinde de görülmüş, durum buğdayında 2021 yılında 198 kg/da'a kadar düşen verim 2022 yılında 278 kg/da'a yükselmiştir (Çizelge 1). 2021 yılında kuraklık, olumsuz iklim koşulları ve özellikle bitkinin gelişme döneminde yağışların yetersiz kalması buğday üretim ve verimini olumsuz etkilemiştir. Buna karşılık 2024 yılında uygun iklim koşulları ve yeterli yağışla birlikte verim yeniden yükselmiştir. Ekiliş alanının Türkiye toplamındaki payının dönem boyunca yaklaşık %3,5 düzeyinde korunmasına rağmen üretimdeki payın %2,22 ile %3,16 arasında değişmesi, Sivas buğday üretiminde yıllara bağlı verim farklılıklarının üretim miktarı üzerinde etkili olduğunu göstermektedir.

Çizelge 1. Sivas ili buğday üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Durum buğdayı verimi (kg/da)	Diğer buğday verimi (kg/da)
2020	2.388.579	3,45	585.838	2,86	296	259	245
2021	2.370.845	3,52	391.692	2,22	262	198	163
2022	2.389.678	3,61	585.931	2,97	298	278	243
2023	2.461.991	3,60	604.399	2,75	322	228	247
2024	2.524.438	3,59	658.284	3,16	296	261	261

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Arpa (*Hordeum vulgare* L.) Üretimi

Arpa, dünyada geniş alanlarda yetiştirilen ve özellikle hayvan besleme, malt üretimi ve gıda amaçlı kullanımlarıyla önem taşıyan temel tahıllardan biridir. Farklı çevresel koşullara uyum gösterebilmesi ve su yetersizliğine karşı geliştirdiği adaptasyon özellikleri, arpayı kurak ve yarı kurak üretim alanları açısından önemli hâle getirmektedir (Elakhdar vd., 2022). Türkiye'de arpa, kullanım çeşitliliğinin yanı sıra özellikle karma yem sanayisi ve hayvancılıkla ilişkisi nedeniyle tarımsal üretimde önemli bir konuma sahiptir (Kızılcan ve Altuntaş, 2025). Sivas'ta da geniş ekiliş alanları ve hayvancılıkla olan bağlantısı nedeniyle kuru tarım ürün deseninin temel tahıllarından biridir; buğdayda olduğu gibi arpa üretiminde de yağmur suyunun önemi Sivas koşullarında yapılan çalışmalarla ortaya konulmuştur (Polat Bulut ve Topal Canbaz, 2022). Bu özellikleri nedeniyle arpanın Sivas kuru tarımındaki konumunun, ekiliş alanı ile birlikte üretim ve verimdeki yıllar arası değişimler üzerinden değerlendirilmesi önem taşımaktadır.

2020-2024 dönemindeki üretim seyri değerlendirildiğinde, arpada ekiliş alanının yaklaşık 1,26-1,37 milyon dekar arasında değiştiği ve 2024 yılında dönem içerisindeki en yüksek düzeye ulaştığı görülmektedir. Üretim miktarı ise aynı ölçüde istikrarlı olmamış; 2021 yılındaki 204.746 tonluk üretimin ardından 2022 yılında yeniden 325.430 tona yükselmiş ve 2024 yılında 339.970 tona ulaşmıştır (Çizelge 2). Bu değişimde verim önemli bir rol oynamıştır. Sivas'ta arpa verimi 2020 yılında 255 kg/da iken 2021 yılında 161 kg/da'a gerilemiş; aynı dönemde kuraklık, yetersiz yağış, yüksek sıcaklıklar ve bazı bölgelerde görülen don olayları bitkinin gelişimini olumsuz etkilemiştir. Bir önceki yıla göre verim kaybı Türkiye genelinde %32,5 iken Sivas'ta %36,9 olarak gerçekleşmiştir. Sonraki yıllarda verimin yeniden yükselmesiyle birlikte üretim miktarı da toparlanmıştır.

Çizelge 2. Sivas ili arpa üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	1.283.095	4,14	326.682	3,94	268	255
2021	1.269.679	4,01	204.746	3,56	181	161
2022	1.295.675	4,05	325.430	3,83	266	251
2023	1.262.300	3,85	286.214	3,11	281	227
2024	1.369.611	4,21	339.970	4,20	249	248

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Yulaf (*Avena sativa* L.) Üretimi

Yulaf, geleneksel olarak hayvan beslemede kullanılan bir tahıl olmakla birlikte son yıllarda insan beslenmesindeki kullanım alanlarının genişlemesiyle birlikte önemi artan ürünlerden biridir. Tanesinin protein kalitesi, lif içeriği ve çeşitli fonksiyonel bileşenler bakımından zengin olması yulafın gıda amaçlı kullanımını da güçlendirmiştir (Karaman vd., 2020; Rasane vd., 2015). Türkiye'de yulaf hem tane ve yem amacıyla hem de insan beslenmesinde değerlendirilebilmekte, farklı kullanım alanları nedeniyle üretim açısından dikkat çeken serin iklim tahılları arasında yer almaktadır. Sivas'ta ise yulafın son yıllardaki üretim gelişimi, ürünün kuru tarım deseni içerisindeki değişen konumunun değerlendirilmesini önemli hâle getirmektedir.

Bu çerçevede yulaf ekiliş alanı 2020 yılındaki 138.412 dekardan 2024 yılında 252.712 dekara yükselerek beş yıllık dönemde belirgin bir genişleme göstermiştir. Üretim miktarı da genel olarak aynı yönde gelişmiş; 2021 yılındaki düşüşün ardından 2023 yılında 76.718 tonla dönem içerisindeki en yüksek seviyeye ulaşmıştır. Böylece Sivas'ın Türkiye yulaf üretimindeki payı %12,61'den %18,98'e çıkmıştır (Çizelge 3). Yulaf üretimindeki genel artışa rağmen 2021 yılı diğer tahıllarda olduğu gibi düşük verimle ayrışmaktadır. Kuraklık ve yetersiz yağışın etkisiyle verim 173 kg/da'a gerilemiş, izleyen dönemde ise yeniden yükselerek 2023 yılında 313 kg/da'a ulaşmıştır.

Çizelge 3. Sivas ili yulaf üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	138.412	12,22	39.653	12,61	278	286
2021	162.702	11,88	28.077	10,17	202	173
2022	221.664	16,10	59.191	16,22	265	267
2023	245.217	17,74	76.718	18,71	297	313
2024	252.712	17,70	74.004	18,98	273	293

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Çavdar (*Secale cereale* L.) Üretimi

Çavdar, dünya genelinde buğday ve arpaya göre daha sınırlı üretim hacmine sahip olmakla birlikte tane ve yem amacıyla değerlendirilebilen önemli bir serin iklim tahılıdır. Soğuğa, kuraklığa ve düşük verimli toprak koşullarına karşı yüksek uyum gösterebilmesi, çavdarın çevresel stresin belirgin olduğu üretim alanlarında önemini artırmaktadır (Newell ve Butler, 2013). Türkiye'de üretimi daha sınırlı olmakla birlikte özellikle uygun çevre koşullarına sahip bölgelerde ürün çeşitliliğinin korunması bakımından değerlendirilmektedir. Bu özellikler, üretim hacmi diğer tahıllara göre daha sınırlı olan çavdarın Sivas kuru tarımındaki yerinin yıllar arasındaki alan, üretim ve verim değişimleriyle birlikte değerlendirilmesini önemli hâle getirmektedir.

Bu kapsamda 2020-2024 dönemindeki üretim verileri incelendiğinde, çavdar ekiliş alanının 2022 yılında 11.904 dekarla en yüksek düzeye ulaştığı ve sonraki yıllarda kısmen gerilediği görülmektedir. Üretim miktarı da benzer biçimde yıllar arasında dalgalanmış; 2021 yılında 1.882 tona düşen üretim 2023 yılında 3.204 tona yükselmiştir. Sivas'ın Türkiye çavdar üretimindeki payı ise dönem boyunca yaklaşık %1 düzeyinde kalmıştır (Çizelge 4). Verimdeki en belirgin düşüş 2021 yılında gerçekleşmiş ve 182 kg/da'a kadar gerilemiştir. Kuraklık ve yağış yetersizliğinin etkili olduğu bu dönemin ardından verim yeniden yükselerek 2023 ve 2024 yıllarında 279 kg/da düzeyine ulaşmıştır.

Çizelge 4. Sivas ili çavdar üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	9.411	0,90	2.708	0,92	283	288
2021	10.353	1,04	1.882	0,94	200	182
2022	11.904	1,22	3.081	1,13	279	259
2023	11.496	1,16	3.204	1,05	308	279
2024	10.167	1,12	2.835	1,10	282	279

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

SİVAS İLİNDE KURU TARIMDA YETİŞTİRİLEN BAKLAGİL ÜRÜNLERİ

Tahılların yanı sıra baklagiller de Sivas'ın kuru tarım ürün deseninin bir parçasını oluşturmaktadır. Bununla birlikte incelenen baklagiller aynı gelişim eğilimini göstermemiş; nohut üretim alanı ve miktarı artarken yeşil mercimekte dalgalı bir yapı, kırmızı mercimekte ise belirgin bir daralma ortaya çıkmıştır.

Nohut (*Cicer arietinum* L.) Üretimi

Nohut, dünya genelinde özellikle kurak ve yarı kurak bölgelerde yetiştirilen önemli yemeklik tane baklagillerden biridir. İnsan beslenmesinde protein kaynağı olması ve yağışa dayalı sistemlerde

yetiştirilebilmesi nedeniyle kuru tarım açısından önem taşımaktadır. Buna karşılık kuraklık, nohut üretimini ve verimini sınırlandıran başlıca abiyotik streslerden biri olarak değerlendirilmektedir (Karkee vd., 2026). Türkiye'de nohut, üretim ve tüketim alışkanlıkları bakımından temel yemeklik tane baklagillerden biri olup tarımsal üretim ve dış ticaret açısından da önem taşımaktadır (Berk ve Uçum, 2019). Sivas koşullarında nohut yetiştiriciliğinin uzun süredir araştırmalara konu olması da ürünün bölgesel önemini desteklemektedir (Karagüllü ve Sencar, 1995). Bu bağlamda son beş yıllık üretim verileri, nohutun Sivas kuru tarımındaki güncel gelişiminin ortaya konulmasına olanak sağlamaktadır.
Nitekim nohut ekiliş alanı 2021 yılındaki sınırlı gerilemenin ardından yeniden genişlemiş ve 2024 yılında 96.272 dekara ulaşmıştır. Üretim miktarı da aynı yönde gelişerek 5.105 tonluk 2021 değerinden 2024 yılında 10.620 tona yükselmiştir. Buna paralel olarak Sivas'ın Türkiye toplam nohut ekiliş alanındaki ve üretimindeki payı da artmıştır (Çizelge 5). Verim 2021 yılında 71 kg/da ile dönem içerisindeki en düşük seviyede gerçekleşmiş; kuraklık ve olumsuz iklim koşulları bu düşüşte etkili olmuştur. İzleyen yıllarda verimin yeniden yükselmesi, ekiliş alanındaki genişlemeyle birlikte toplam üretimdeki artışı desteklemiştir. Son yıllardaki alan ve üretim artışı Tarım Alanlarının Etkinleştirilmesi Projesi (TAKE) ile de ilişkilendirilmektedir.

Çizelge 5. Sivas ili nohut üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	73.884	1,44	6.489	1,03	123	88
2021	71.505	1,47	5.105	1,07	97	71
2022	86.549	1,89	6.961	1,20	127	80
2023	85.921	1,87	8.577	1,48	126	100
2024	96.272	2,09	10.620	1,85	125	110

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Yeşil Mercimek (*Lens culinaris* Medik) Üretimi

Mercimek, yüksek protein içeriğinin yanı sıra demir, çinko, lif ve çeşitli besin bileşenlerini sağlaması nedeniyle insan beslenmesi ve gıda güvenliği açısından önemli yemeklik tane baklagillerden biridir. Yarı kurak ve marjinal üretim alanlarında yetiştirilebilmesi mercimeğin kuru tarım sistemleri açısından önemini artırırken, kuraklık üretim performansını sınırlandırabilmektedir (Zeroual vd., 2023). Türkiye'de yeşil ve kırmızı mercimek, nohut ve kuru fasulyeyle birlikte başlıca yemeklik tane baklagiller arasında yer almakta ve tahıllardan sonra tarla bitkileri üretiminin önemli bileşenlerinden birini oluşturmaktadır (Burhan ve Yılmaz Soydan, 2023). Sivas'ta daha sınırlı alanlarda yetiştirilen yeşil mercimeğin kuru tarım ürün desenindeki konumunun ortaya konulabilmesi için ekiliş alanı, üretim ve verim göstergelerinin yıllar içerisindeki değişiminin birlikte değerlendirilmesi önem taşımaktadır.
Bu göstergeler birlikte ele alındığında, yeşil mercimek ekiliş alanının 2021 yılında 6.003 dekara kadar yükseldiği, ancak bu artışın sonraki yıllarda devam etmediği görülmektedir. Üretim miktarı da aynı yıl 449 tonla en yüksek düzeye ulaşmış ve izleyen dönemde azalmıştır. Benzer bir değişim Türkiye üretimindeki payda da görülmüş; 2021 yılında %1,28'e ulaşan pay 2024 yılında yeniden %0,46'ya gerilemiştir (Çizelge 6). Verim değerleri de istikrarlı bir artış göstermemiştir. 2020 yılında 102 kg/da olan verim 2023 yılında 67 kg/da'a kadar düşmüş ve 2024 yılında 75 kg/da olarak gerçekleşmiştir. Ekiliş alanı, üretim ve verimdeki bu değişimler yeşil mercimek üretiminin incelenen dönemde dalgalı bir yapıya sahip olduğunu göstermektedir.

Çizelge 6. Sivas ili yeşil mercimek üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	1.729	0,46	176	0,42	112	102
2021	6.003	1,25	449	1,28	73	75
2022	4.080	0,95	340	0,76	105	83
2023	3.877	0,87	260	0,52	112	67
2024	4.339	0,62	327	0,46	101	75

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

Kırmızı Mercimek (*Lens culinaris* Medik.) Üretimi

Kırmızı mercimek de beslenme değeri ve kuru koşullara uyum yeteneği bakımından önemli yemeklik tane baklagiller arasında yer almaktadır. Mercimeğin özellikle yarı kurak alanlardaki üretim sistemlerinde yer alabilmesi, ürünü kuru tarım açısından önemli kılmaktadır (Zeroual vd., 2023). Türkiye, mercimeğin hem üretimi hem de işlenmesi ve pazarlanması açısından uzun süredir önemli bir üretim yapısına sahip olup yeşil ve kırmızı mercimeğin üretim, tüketim ve dış ticaret yapısı tarımsal ekonomi açısından da değerlendirilmektedir (Küzeci vd., 2019). Sivas'ta daha sınırlı bir üretim hacmine sahip olan kırmızı mercimeğin son yıllardaki gelişiminin ortaya konulması, ürünün kuru tarım deseni içerisindeki konumunun değerlendirilmesi açısından önem taşımaktadır.

Bu doğrultuda 2020-2024 dönemi incelendiğinde, kırmızı mercimek ekiliş alanının 1.282 dekardan 308 dekara gerilediği, üretim miktarının ise 140 tondan 34 tona düştüğü görülmektedir. Türkiye üretimindeki payın %0,04'ten %0,01'e gerilemesi de ürünün Sivas'taki göreli ağırlığının azaldığını göstermektedir (Çizelge 7). Buna karşılık verim değerleri ekiliş alanındaki daralma kadar belirgin bir gerileme göstermemiştir. Verim 2023 yılında 118 kg/da'a yükselmiş ve 2024 yılında 110 kg/da olarak gerçekleşmiştir. Bu nedenle kırmızı mercimekte toplam üretimdeki düşüşün temelinde verim kaybından çok ekiliş alanındaki daralma bulunmaktadır.

Çizelge 7. Sivas ili kırmızı mercimek üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Türkiye verimi (kg/da)	Sivas verimi (kg/da)
2020	1.282	0,06	140	0,04	157	109
2021	385	0,01	35	0,02	88	91
2022	347	0,01	32	0,01	133	92
2023	331	0,01	39	0,01	152	118
2024	308	0,01	34	0,01	167	110

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

SİVAS İLİNDE YEM BİTKİLERİ ÜRETİMİ

Korunga (*Onobrychis viciifolia* Scop.) Üretimi

Korunga, kurak ve yarı kurak koşullara uyum gösterebilen çok yıllık bir yem baklagili olup hayvan besleme, toprak verimliliği ve düşük yağış koşullarında üretim potansiyeli bakımından önem taşımaktadır. Derin kök sistemi, düşük yağışlı alanlarda kuraklığa uyumuna katkı sağlamakta; yüksek palatabilitesi (lezzet değeri) ve ruminant beslemedeki kullanım özellikleri nedeniyle değerli bir kaba yem kaynağı olarak değerlendirilmektedir (Mora-Ortiz ve Smith, 2018). Türkiye'de korunganın kaba yem kalitesi üzerine yapılan çalışmalar da ürünün hayvan besleme açısından önemli bir kaynak olduğunu göstermektedir (Özdemir vd., 2023). Sivas'ta yem bitkisi yetiştiriciliğinin hayvancılıkla olan ilişkisi içerisinde korunga önemli ürünlerden biri olup, Sivas'tan elde edilen yerel korunga popülasyonlarının besleme değerlerinin doğrudan araştırmalara konu olması da ürünün bölgesel önemini desteklemektedir (Altıntaş vd., 2017; Ülger ve Kaplan, 2016). Korunganın kuru koşullara uyumu ve Sivas hayvancılığı açısından taşıdığı bu önem, ildeki üretim alanı, toplam üretim ve verim değişimlerinin birlikte değerlendirilmesini gerekli kılmaktadır.

Bu kapsamda 2020-2024 dönemi incelendiğinde, korunga ekiliş alanının 185.800 dekardan 142.819 dekara gerileyerek dönem boyunca daraldığı görülmektedir. Üretim miktarı da genel olarak aynı yönde gelişerek 104.085 tondan 79.556 tona düşmüştür. Buna karşın Sivas'ın Türkiye toplam korunga alanındaki payı %10,65'ten %11,50'ye yükselmiş ve üretimdeki payı yaklaşık %5 düzeyinde korunmuştur (Çizelge 8).

Verim 2021 yılında 443 kg/da'a kadar gerilemiş, daha sonra düzenli olarak yükselerek 2024 yılında 557 kg/da'a ulaşmıştır. Böylece üretim alanındaki daralmaya rağmen birim alan veriminde 2021 sonrasında belirgin bir toparlanma meydana gelmiştir.

Çizelge 8. Sivas ili korunga üretim verilerinin yıllara göre değişimi

Yıl	Ekiliş alanı (da)	Türkiye ekiliş alanındaki payı (%)	Üretim (ton)	Türkiye üretimindeki payı (%)	Sivas verimi (kg/da)
2020	185.800	10,65	104.085	5,38	560
2021	183.405	10,11	81.255	5,25	443
2022	183.146	11,32	92.066	5,15	503
2023	169.343	11,59	88.390	5,59	522
2024	142.819	11,50	79.556	5,42	557

Kaynak: TÜİK, Bitkisel Üretim İstatistikleri (2020-2024)

GENEL DEĞERLENDİRME VE SONUÇ

Sivas'ta 2020-2024 döneminde kuru tarım kapsamında değerlendirilen ürünlerin üretim yapısı birlikte ele alındığında, tahılların ürün deseninde belirgin bir ağırlığa sahip olduğu görülmektedir. Buğday ve arpa geniş ekiliş alanlarını büyük ölçüde korurken, üretim ve verim değerleri yıllara göre daha değişken bir yapı göstermiştir. Özellikle 2021 yılında buğday, arpa, yulaf ve çavdarda görülen düşük verim değerleri, kuru tarım koşullarında yıllık iklim ve yağış koşullarının üretim performansı üzerindeki önemini ortaya koymaktadır.

Tahıl grubu içerisinde yulaf, ekiliş alanı ve üretim miktarındaki artışla diğer ürünlerden ayrılmıştır. Sivas'ın Türkiye yulaf üretimindeki payının dönem içerisinde yükselmesi, yulafın ildeki kuru tarım ürün deseni içerisindeki göreli öneminin arttığını göstermektedir. Çavdar ise daha sınırlı bir üretim hacmine sahip olmasına rağmen kuru ve soğuk koşullara uyumu nedeniyle ürün çeşitliliğinin korunması açısından önem taşımaktadır. Baklagillerde ürünlere göre farklı eğilimler ortaya çıkmıştır. Nohut ekiliş alanı, üretim miktarı ve verim bakımından dönem sonunda daha yüksek değerlere ulaşırken, yeşil mercimekte yıllar arasında dalgalı bir yapı görülmüştür. Kırmızı mercimekte ise üretim alanının belirgin biçimde daralması toplam üretim miktarını da sınırlandırmıştır. Bu farklılık, aynı ürün grubu içerisindeki türlerin dahi Sivas koşullarında benzer üretim eğilimleri göstermediğini ortaya koymaktadır. Korunga üretiminde ekiliş alanı ve toplam üretim miktarının azalmasına rağmen Sivas'ın Türkiye toplamındaki göreli payının korunması, ürünün il açısından önemini sürdürdüğünü göstermektedir. Verimin 2021 sonrasında yeniden yükselmesi ise üretim miktarındaki gerilemenin yalnızca birim alan verimiyle değil, ekiliş alanındaki daralmayla da ilişkili olduğunu ortaya koymaktadır.

Genel olarak Sivas'ın kuru tarım ürün deseninde geniş alanlı ve süreklilik gösteren tahıl üretimi ile farklı yönlerde değişim gösteren baklagil ve yem bitkileri üretiminin birlikte bulunduğu görülmektedir. Ürünler arasındaki ekiliş alanı, üretim miktarı ve verim farklılıkları, kuru tarım ürün deseninin tek bir üretim göstergesi üzerinden değerlendirilmesinin yeterli olmadığını ortaya koymaktadır. Bu nedenle üretim planlamasında ürünlerin yıllar arasındaki verim değişkenliği, ekiliş alanındaki gelişim ve kuru koşullara uyum özelliklerinin birlikte dikkate alınması önem taşımaktadır.

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KEKİK VE LAVANTA UÇUCU YAĞLARININ SUDA YAĞ EMÜLSİYONU (EW) FORMÜLASYONUNUN MELOİDOGYNE İNCOGNİTA ÜZERİNDEKİ IN VİTRO NEMATİSİDAL ETKİNLİĞİ

IN VITRO NEMATICIDAL EFFICACY OF OIL-IN-WATER EMULSION (EW) FORMULATIONS OF THYME AND LAVENDER ESSENTIAL OILS AGAINST MELOIDOGYNE INCOGNITA

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Özet
Kök-ur nematodları (*Meloidogyne* spp.), tarımsal üretimde önemli verim ve kalite kayıplarına yol açan ekonomik açıdan en zararlı bitki paraziti etmenler arasındadır. Sentetik nematisitlerin olumsuz çevre ve sağlık etkileri nedeniyle, biyolojik kökenli ve çevre dostu alternatiflerin geliştirilmesi önem kazanmıştır. Bu çalışmada, Ankara Zirai Mücadele Merkez Araştırma Enstitüsü Zirai Mücadele İlaçları Bölümünden temin edilen, kekik ve lavanta uçucu yağlarının suda yağ emülsiyonu (EW) formülasyonlarının, *Meloidogyne incognita* ikinci dönem larvalarına (J2) karşı nematisidal etkinliğinin *in vitro* koşullarda belirlenmesi amaçlanmıştır. Kekik ve lavanta uçucu yağlarının kimyasal bileşimleri GC-MS analiz sonuçlarına göre değerlendirilmiştir. Uçucu yağların EW formülasyonları, *M. incognita* J2'lerine karşı 2000 ppm (2 µL mL^{-1}) konsantrasyonda tek doz kontakt etki denemesine tabi tutulmuştur. Nematisidal etkinlik, uygulamadan 24, 48 ve 72 saat sonra belirlenen J2 ölümleri üzerinden değerlendirilmiştir. GC-MS analizleri sonucunda, kekik uçucu yağının ana bileşenlerinin carvacrol (%73,78), linalool (%5,93), γ-terpinene (%4,69) ve p-cymene (%3,87) olduğu; lavanta uçucu yağının ise linalool (%43,33), linalyl acetate (%19,82), camphor (%6,66) ve 1,8-cineole (%4,38) içerdiği belirlenmiştir. Deneme sonuçlarına göre kekik uçucu yağı formülasyonu, *M. incognita* J2'lerine karşı 24, 48 ve 72 saat sonunda sırasıyla %77,7, %86,0 ve %89,2 oranlarında ölüm meydana getirmiştir. Lavanta uçucu yağı formülasyonunda ise aynı sürelerde larva ölüm oranları sırasıyla %21,0, %33,2 ve %50,9 olarak belirlenmiştir. Kontrol grubunda mortalite oranı ihmal edilebilir düzeyde (<%0,5) kalmıştır. Elde edilen bulgular, her iki uçucu yağ formülasyonunun da süreye bağlı olarak artan oranlarda *M. incognita* J2'leri üzerinde nematisidal etki gösterdiğini, kekik uçucu yağının ise lavantaya kıyasla daha yüksek etkinlik sergilediğini ortaya koymuştur. Özellikle kekik formülasyonunda 72 saat sonunda ulaşılan %89,2'lik ölüm oranı, bu uçucu yağın kök-ur nematodlarına karşı alternatif bir mücadele materyali olarak araştırılabileceğini göstermektedir. Bununla birlikte, uçucu yağların nematod mücadelesinde kullanılabilirliğinin ortaya konulması için farklı konsantrasyonlarda doz-cevap çalışmalarına ve sera koşullarındaki etkinlik değerlendirmelerine ihtiyaç bulunmaktadır.
Anahtar kelimeler: Kök-ur nematodu, *Origanum*, *Lavandula*, GC-MS analizi, nematisidal aktivite

Abstract
Root-knot nematodes (*Meloidogyne* spp.) are among the most economically destructive plant-parasitic pests, causing substantial yield and quality losses in agricultural production. Due to the adverse

environmental and human health impacts of synthetic nematicides, the development of eco-friendly, bio-based alternatives has gained increasing importance. This study aimed to determine the *in vitro* nematicidal efficacy of oil-in-water emulsion (EW) formulations of thyme and lavender essential oils, obtained from the Plant Protection Products Department of the Directorate of Plant Protection Central Research Institute (Ankara), against the second-stage juveniles (J2) of *Meloidogyne incognita*. The chemical compositions of the essential oils were characterized via GC-MS analysis. The EW formulations were evaluated in a single-dose contact toxicity assay at a concentration of 2000 ppm (2 µL mL^{-1}) against *M. incognita* J2s, and nematicidal activity was recorded based on juvenile mortality at 24, 48, and 72 hours post-application. GC-MS analyses revealed that the major constituents of thyme essential oil were carvacrol (73.78%), linalool (5.93%), γ-terpinene (4.69%), and p-cymene (3.87%), whereas lavender essential oil primarily comprised linalool (43.33%), linalyl acetate (19.82%), camphor (6.66%), and 1,8-cineole (4.38). The bioassay results demonstrated that the thyme essential oil formulation induced 77.7%, 86.0%, and 89.2% mortality in *M. incognita* J2s after 24, 48, and 72 hours, respectively. In comparison, the lavender formulation resulted in mortality rates of 21.0%, 33.2%, and 50.9% across the same exposure intervals, while control mortality remained negligible (<0.5%). These findings indicate that both formulations exhibited time-dependent nematicidal activity, with thyme essential oil displaying significantly superior efficacy compared to lavender. In particular, the 89.2% mortality achieved by the thyme formulation at 72 hours underscores its potential as an alternative control agent against root-knot nematodes. Nonetheless, further dose-response bioassays at varying concentrations and greenhouse efficacy trials are necessary to fully elucidate their practical applicability in nematode management.

Keywords: Root-knot nematode, *Origanum, Lavandula,* GC-MS analysis, nematicidal activity

GİRİŞ

Bitki paraziti nematodlar, tarımsal üretimde verim ve kalite kayıplarına neden olan en önemli biyotik stres faktörlerinden biri olarak kabul edilmektedir. Bu grup içerisinde kök-ur nematodları (*Meloidogyne* spp.), geniş konukçu aralıkları, yüksek üreme kapasiteleri ve oluşturdukları ekonomik kayıplar nedeniyle öne çıkmaktadır (Bagnaresi vd., 2013). Nitekim kök-ur nematodlarının dünya genelinde tüm bitki kayıplarının yaklaşık %14'ünden sorumlu olduğu ve bunun yıllık olarak yaklaşık 100 milyar dolara karşılık geldiği bildirilmektedir (Bagnaresi vd., 2013); diğer tahminler kök-ur nematodlarının yol açtığı kayıpların yılda 157 milyar dolar düzeyine ulaşabileceğini göstermektedir (Atif vd., 2023). Yalnızca *Meloidogyne incognita* türünün tek başına yılda 100 milyar dolarlık bir kayba neden olduğu tahmin edilmektedir (Subedi vd., 2020). Bu tablo, kök-ur nematodlarının gıda güvenliği açısından taşıdığı riski açık biçimde ortaya koymaktadır (Atif vd., 2023).

Meloidogyne incognita, sahip olduğu geniş konukçu yelpazesi ve yüksek üreme hızı nedeniyle en zararlı kök-ur nematodu türlerinden biri olarak değerlendirilmektedir (Kihika vd., 2017). Bu tür, domates, patlıcan, biber ve patates gibi ekonomik değeri yüksek Solanaceae türleri başta olmak üzere 2000'den fazla bitki türünün köklerini enfekte edebilmektedir (Arunachalam vd., 2026; Kihika vd., 2017). Enfeksiyon, ikinci dönem larva (J2) dönemindeki bireylerin kök dokusuna girmesiyle başlamakta; nematod kökün vasküler dokularını işgal ederek beslenme bölgesinde çok çekirdekli "dev hücreler" oluşturmaktadır (Kihika vd., 2017). Bu süreç sonucunda konukçu bitkinin su ve besin elementi alımı engellenmekte, bitkide zayıf gelişim, verim azalması ve köklerde tipik urlar meydana gelmektedir (Atif vd., 2023; Kihika vd., 2017). Kök-ur nematodlarının neden olduğu zarar yalnızca doğrudan verim kaybıyla sınırlı kalmamakta, aynı zamanda toprak kaynaklı diğer patojenlerle birlikte karmaşık hastalık komplekslerinin oluşumuna zemin hazırlamaktadır (Arunachalam vd., 2026). Zararın büyüklüğü ekolojik ve iklimsel koşullara bağlı olarak değişmekle birlikte, bazı durumlarda verim kayıplarının %50'ye kadar çıkabildiği ve özellikle yüksek değerli sebzelerde kayıpların %100'e ulaşabildiği rapor edilmiştir (Kihika vd., 2017; Santos vd., 2013).

Kök-ur nematodlarına karşı mücadelede günümüze kadar ağırlıklı olarak sentetik nematisitler, dayanıklı çeşit kullanımı, münavebe, toprak solarizasyonu ve biyolojik kontrol gibi yöntemlerden yararlanılmıştır (Hussain vd., 2016; Subedi vd., 2020). Sentetik nematisit uygulamaları hızlı ve yüksek etkinlik sağlamasına karşın, yüksek maliyetleri, hedef dışı organizmalar üzerindeki olumsuz etkileri ve insan sağlığı ile çevre açısından taşıdığı riskler nedeniyle giderek daha fazla sorgulanmaktadır (Hussain vd., 2016). Ayrıca bu kimyasalların yoğun ve tekrarlı kullanımı, hedef nematod popülasyonlarında direnç gelişimine yol açabilmektedir (Arunachalam vd., 2026). Çok sayıda sentetik nematisitin yasaklanması

veya kullanımının önemli ölçüde kısıtlanması, alternatif ve sürdürülebilir mücadele stratejilerine duyulan ihtiyacı artırmıştır (Andrés vd., 2012; Santos vd., 2013). Bu bağlamda, bitki kaynaklı doğal bileşikler ve özellikle uçucu yağlar, düşük memeli toksisiteleri ve çevresel kalıcılıklarının sınırlı olması nedeniyle biyolojik kontrol ajanlarıyla uyumlu, umut verici biyopestisit adayları olarak öne çıkmaktadır (Andrés vd., 2012).

Uçucu yağlar, aromatik bitkilerin sekonder metabolitleri olup terpenler, terpenoidler ve çeşitli aromatik ve alifatik bileşiklerden oluşan kompleks karışımlardır (Sarri vd., 2024). Nematodlar üzerindeki etkileri; plazma zarı geçirgenliğinin bozulması, sinir sisteminin etkilenmesi, hücre içi redoks dengesinin bozulması ve apoptoz ile ilişkili sinyal yolaklarının tetiklenmesi gibi çoklu mekanizmalara dayanmaktadır (Sarri vd., 2024). Yapılan derlemelerde nematisidal etkinliği araştırılan uçucu yağların büyük bölümünün Lamiaceae familyasına ait olduğu (%32) ve bunu Asteraceae (%11), Apiaceae (%9) ile Poaceae (%8) familyalarının izlediği bildirilmiştir (Sarri vd., 2024). Bileşen düzeyinde değerlendirildiğinde geraniol, carvacrol, limonen, öjenol, timol ve pinenin en güçlü nematisidal potansiyele sahip olduğu; etkinliğin büyük ölçüde konsantrasyona bağlı olarak değiştiği vurgulanmaktadır (Sarri vd., 2024). Carvacrol ve timolün nematod ölümüne, tyramin reseptörüne bağlı bir sinyal kaskadı aracılığıyla yol açabildiği (Andrés vd., 2012), carvacrolün ise nematodun nöromusküler sistemindeki nikotinik asetilkolin reseptörleri (nAChR) ile etkileşerek hareketi bozabildiği bildirilmiştir (Sarri vd., 2024).

Bu çerçevede, uçucu yağların nematisidal aktivitesinin değerlendirilmesinde Lamiaceae familyasına ait türler özel bir önem taşımaktadır. Fenolik monoterpen içeriği bakımından zengin *Origanum* türleri ile oksijenli monoterpen ve ester bakımından zengin *Lavandula* türleri, farklı kimyasal profilleri sayesinde karşılaştırmalı çalışmalar için uygun modeller oluşturmaktadır. Nitekim *Lavandula intermedia* uçucu yağının ana bileşeni olan linaloolün, *M. incognita* J2'leri ve yumurtaları üzerinde etkili olduğu; larva ölümü, yumurta açılımının engellenmesi, gal ve yumurta sayısında azalma gibi sonuçlar oluşturduğu bildirilmiştir (Sarri vd., 2024). Diğer yandan, *M. incognita*'nın, *Monarda didyma* ve *M. fistulosa* uçucu yağlarının ana bileşeni olan carvacrole karşı belirgin bir duyarlılık gösterdiği; 24 saatlik uygulama sonunda LC50 değerinin 14,2 $\mu g\ mL^{-1}$ olduğu, bu konsantrasyonun J2'lerde %82 ölüme yol açtığı ve 48 saatlik maruziyet sonunda yumurta açılımının %4,1'e kadar gerilediği belirtilmektedir (Sarri vd., 2024). Uçucu yağların biyolojik aktivitelerinin yalnızca tek bir baskın bileşene bağlanması ise doğru bir yaklaşım değildir; ana ve minör bileşenler arasındaki olası additif, sinerjistik veya antagonistik etkileşimlerin de etkinlik üzerinde belirleyici olduğu bilinmektedir (Sarri vd., 2024). Ayrıca uçucu yağ esaslı ticari nematisitlerin henüz pazar payı kazanmadığı ve mevcut sentetik nematisitlerin kullanımdan çekilmesi nedeniyle uçucu yağ formülasyonlarına dayalı yeni ürünlerin geliştirilmesine açık bir ihtiyaç bulunduğu vurgulanmaktadır (Andrés vd., 2012). Ancak uçucu yağların yüksek hidrofobiklik, suda düşük çözünürlük ve yüksek uçuculuk gibi doğal özellikleri, doğrudan kullanımlarını ve biyolojik etkinliklerinin sürekliliğini sınırlamaktadır (Singh ve Pulikkal, 2022). Bu dezavantajların üstesinden gelmek amacıyla, biyolojik olarak parçalanabilir polimerler veya yüzey aktif maddeler kullanılarak hazırlanan mikro/nano emülsiyon ve kapsülleme teknikleriyle aktif maddelerin degradasyon ve buharlaşmadan korunması ve kontrollü salınımının sağlanması önerilmektedir (Andrés vd., 2012; Sarri vd., 2024). Özellikle nano emülsiyonlar, kinetik olarak stabil sistemler olup damlacık boyutlarının 50–200 nm aralığında olması sayesinde yüksek yüzey alanı ve artırılmış stabilite sunmaktadır (Campolo vd., 2020). Bu tür formülasyonların, uçucu yağların sulama suyunda dağılabilmesine, bitki köklerine hızlı yapışma ve penetrasyonuna ve toprakta daha uzun süre kalmasına olanak tanıdığı; nano emülsiyonların nematodlar üzerindeki etkinliğinin, küçültülmüş damlacık boyutundan kaynaklanan gelişmiş stabilite sayesinde doğrudan uçucu yağlara kıyasla üstün olduğu bildirilmiştir (Sarri vd., 2024). Benzer şekilde, uçucu yağların suda yağ tipi emülsiyonlar biçiminde formüle edilmesinin, damlacık boyutu ve stabilite optimizasyonu yoluyla tarımsal uygulamalarda etkinliği artırdığı ve püskürtme kayıplarını azalttığı gösterilmiştir (Heng, 2025; Llinares vd., 2017).

Bu bilgiler ışığında, biyolojik etkinliği kanıtlanmış uçucu yağların uygun formülasyonlara dönüştürülerek etkinliğinin ve kullanılabilirliğinin artırılması, sürdürülebilir nematod mücadelesi açısından önemli bir araştırma alanını oluşturmaktadır. Bu çalışmada, fenolik monoterpen bakımından zengin kekik (*Origanum onites*) ve oksijenli monoterpen-ester bakımından zengin lavanta (*Lavandula intermedia*) uçucu yağlarından elde edilen suda yağ emülsiyonu formülasyonlarının, *M. incognita* ikinci dönem larvalarına (J2) karşı nematisidal etkinliğinin in vitro koşullarda belirlenmesi amaçlanmıştır. Bu kapsamda, iki uçucu yağın kimyasal kompozisyonları karakterize edilerek, EW formülasyonlarının 24,

48 ve 72 saatlik maruziyet sürelerindeki kontakt etkileri karşılaştırmalı olarak değerlendirilmiştir. Elde edilen bulguların, uçucu yağ esaslı biyopestisit formülasyonlarının geliştirilmesine ve kök-ur nematodlarına karşı sentetik nematisitlere alternatif stratejilerin oluşturulmasına katkı sağlaması beklenmektedir.

MATERYAL VE YÖNTEM

Materyal

Çalışmanın ana materyalini Antalya Batı Akdeniz Tarımsal Araştırma Enstitüsünden elde edilen kekik (*Origanum onites*) ve lavanta (*Lavandula intermedia*) uçucu yağlarının Ankara Zirai Mücadele Merkez Araştırma Enstitüsü Zirai Mücadele İlaçları Bölümünde oluşturulan suda yağ emülsiyonu (EW) formülasyonları ve *Meloidogyne incognita* saf kültürü oluşturmuştur.

Uçucu Yağ Analizi

Kekik ve lavanta suda yağ emülsiyonu formülasyonlarının eldesinde kullanılan uçucu yağların içeriklerinin belirlenmesi için GC/MS ve GC/FID analizi yapılmıştır. GC/MS analizi Innowax FSC (60 m × 0.25 mm, 0.25 µm film kalınlığı) kolonda helium taşıyıcı gazıyla (0.8 mL/min) ve şu sıcaklık programı ile gerçekleştirilmiştir: Fırın sıcaklığı 60 °C'de 10 dakika bekletildikten sonra 220 °C'ye 4 °C/min hızla yükseltilmiş, bu sıcaklıkta 10 dakika sabit tutulduktan sonra 240 °C'ye 1 °C/min hızla yükseltilmiştir. Kütle spektrumları 70 eV'ta kütle/yük (m/z) oranı 35-450 aralığında kaydedilmiştir. GC/FID analizi, GC/MS ile aynı elüsyon sırasını elde etmek amacıyla aynı kolon ve sıcaklık programı kullanılarak gerçekleştirilmiş ve FID dedektör sıcaklığı 300 °C'de tutulmuştur. Bileşenlerin nispi yüzdeleri FID kromatogramlarındaki pik alanlarından hesaplanmıştır. Bileşenlerin tanımlanması, kütle spektrumlarının Wiley ve Adams kütüphaneleriyle karşılaştırılması ve n-alkan serisine göre hesaplanan lineer retansiyon indekslerinin literatür değerleriyle karşılaştırılması yoluyla yapılmıştır mıştır (Polatoğlu vd., 2016).

Meloidogyne incognita Kültürü

Bu çalışmada, Ankara Zirai Mücadele Merkez Araştırma Enstitüsü Nematoloji Laboratuvarı'nda muhafaza edilen *M. incognita* saf kültürü kullanılmıştır. Nematod popülasyonu, kök-ur nematoduna duyarlı bir domates çeşidi olan SC2121 üzerinde çoğaltılmıştır. İki dört gerçek yaprak aşamasındaki domates fideleri, sterilize edilmiş kum-toprak karışımı (85:15, v/v) içeren 550 mL'lik saksılara dikilmiş ve enfekteli domates köklerinden toplanan yumurta paketleri ile inoküle edilmiştir. Bitkiler, yaklaşık sekiz hafta boyunca 25 ± 2 °C sıcaklıkta ve 14:10 saatlik aydınlık:karanlık fotoperiyodunda yetiştirilmiştir. Enfekteli köklerden toplanan yumurta paketleri, 12 cm çapındaki Petri kaplarına yerleştirilen 5 cm çapındaki eleklerin üzerine aktarılmıştır. Yumurta paketlerini örtecek miktarda steril su ilave edilmiştir. Petri kapları 25 ± 1 °C sıcaklıkta inkübe edilmiş; yeni çıkan ikinci dönem larvalar (J2) 24 saatlik aralıklarla toplanmış ve kullanılana kadar 4 °C'de saklanmıştır. Çalışmalarda 24-72 saatlik J2 kullanılmıştır. Denemelerden önce J2 süspansiyonu mikroskop altında sayılmış ve konsantrasyon 100 J2 mL^{-1} olacak şekilde ayarlanmıştır (Evlice ve ark., 2026).

Nematisidal Etki Çalışmaları

Denemelerde 16 kuyucuklu plakalarda 2 µL mL^{-1} konsantrasyonda gerçekleştirildi. Her bir kuyucuğa, yaklaşık 100 adet J2 içeren nematod süspansiyonundan eklenmiş ve üzerlerine kekik ve lavanta preparatlarından (%10 v/v) 20 µl eklenmiştir. Kontrol olarak %1(v/v) distile su kullanılmıştır. Buharlaşmayı azaltmak için plakalar parafilm ile sarılmış ve karanlığı sağlamak için alüminyum folyoya sarılarak 25°C'deki inkübatöre yerleştirilmiştir. Ölü canlı nematodlar 24, 48 ve 72 saat sonra inverted mikroskop altında sayılmıştır. Düz ve ince uzun şekil almış olanlarla baş ve kuyruğu bazen hafifçe bükülmüş olanlar fiziksel olarak uyarıldıklarında bile hareket etmedilerse paralize olarak kabul edilmişlerdir. Nematodların ölü olmadıklarını doğrulamak amacıyla 72 saat sonunda nematodlar 24 saat distile su içerisinde bekletilmiş ve hala aktif olmayanlar ölü olarak kabul edilmiştir (Caboni vd. 2013). Kontrol grubundaki doğal mortaliteyi hesaba katmak amacıyla, düzeltilmiş mortalite oranı Schneider-Orelli formülü kullanılarak hesaplandı (Puntener, 1981). Denemeler tesadüf blokları deneme desenine göre 6 tekerrürlü 2 tekrarlı olarak yürütülmüştür.

SONUÇLAR VE TARTIŞMA

Çalışmada kullanılan kekik ve lavanta suda yağ emülsiyonu (EW) formülasyonlarının eldesinde kullanılan uçucu yağlarının bilşenlerine ait bilgiler Çizelge 1'de verilmiştir. Analiz sonuçlarına göre,

her iki uçucu yağın kimyasal profilinin monoterpenler bakımından zengin olduğu, ancak baskın ana bileşenler açısından belirgin kalitatif ve kantitatif farklılıklar sergilediği belirlenmiştir. *Origanum onites* uçucu yağında toplam 20 bileşen tespit edilmiş olup, yağın temel bileşeninin carvacrol olduğu ve toplam bileşimin %73,78'ini oluşturduğu görülmektedir. Carvacrolü linalool (%5,93), γ-terpinene (%4,69) ve p-cymene (%3,87) izlemiştir. Bunun yanında α-thujene, myrcene, α-terpinene, terpinen-4-ol, borneol ve β-caryophyllene gibi bileşenler daha düşük oranlarda tespit edilmiştir. Bu sonuçlar, *O. onites* uçucu yağının ağırlıklı olarak monoterpenik fenolik bileşiklerden oluşan karakteristik bir kimyasal profile sahip olduğunu göstermektedir. Özellikle carvacrolün yüksek oranda bulunması, bu uçucu yağın biyolojik aktivitesinin değerlendirilmesinde dikkate alınması gereken başlıca kimyasal özelliklerden biridir. *Lavandula intermedia* uçucu yağında ise daha farklı ve bileşenler arasında daha dengeli bir kimyasal dağılım belirlenmiş olup *O. onites*'ten farklı olarak oksijenli monoterpenler ve esterler baskın durumdadır. Uçucu yağın en yüksek orandaki bileşeni linalool (%43,33) olurken, bunu linalyl acetate (%19,82), camphor (%6,66), 1,8-cineole (%4,38) ve α-terpineol (%3,73) izlemiştir. Ayrıca geraniol (%2,18), lavandulyl acetate (%1,91), geranyl acetate (%1,79), trans-ocimene (%2,03) ve β-myrcene (%1,44) gibi bileşenler de belirlenmiştir. Dolayısıyla *L. intermedia* uçucu yağı, linalool ve linalyl acetate bakımından zengin olmasıyla *O. onites* uçucu yağından belirgin şekilde farklı bir kimyasal profil sergilemektedir.

İki uçucu yağ arasındaki bu bileşim farklılığı, söz konusu yağlardan hazırlanan suda yağ emülsiyonu (EW) formülasyonlarının biyolojik aktivitelerinin değerlendirilmesi açısından önem taşımaktadır. *Origanum onites* yağında yüksek oranda bulunan carvacrolün, çeşitli zararlı organizmalar üzerindeki biyolojik aktiviteleri çok sayıda çalışmada ortaya konulmuş olup, bu bileşiğin hücre membranı bütünlüğünü ve membran geçirgenliğini etkileyebildiği bildirilmiştir (Santana vd., 2014; Sarri vd., 2024). Benzer şekilde, *L. intermedia* uçucu yağında baskın olan linalool ve linalyl acetate başta olmak üzere oksijenli monoterpenlerin de farklı biyolojik aktivitelerle ilişkili olduğu bildirilmektedir (Elguea-Culebras vd., 2017; Sancho vd., 2021). Bununla birlikte, uçucu yağların biyolojik etkilerinin yalnızca tek bir baskın bileşene bağlanması doğru olmayıp, ana ve minör bileşenlerin birlikte oluşturduğu kimyasal profil ile bileşenler arasındaki olası additif, sinerjistik veya antagonistik etkileşimlerin de dikkate alınması gerekmektedir (Andrés vd., 2012; Sarri vd., 2024). Bu bağlamda, *O. onites* ve *L. intermedia* uçucu yağlarının farklı kimyasal kompozisyonlara sahip olması, bunlardan hazırlanan EW formülasyonlarının *M. incognita*'ya karşı farklı düzeylerde nematisidal aktivite göstermesini açıklayabilecek faktörlerden biri olarak değerlendirilebilir.

Çizelge 1. *Origanum onites* ve *Lavandula intermedia* uçucu yağlarının içerdiği uçucu yağ bileşenleri

Kekik (*Origanum onites*)		**Lavanta (*Lavandula intermedia*)**	
Uçucu yağ Bileşeni	Alan (%)	Uçucu yağ Bileşeni	Alan (%)
***α*-Pinene**	0,53	Camphene	0,32
***α*-Thujene**	0,81	*β*-Myrcene	1,44
Camphene	0,24	Limonene	1,08
Myrcene	1,26	1,8-Cineole	4,38
***α*-Terpinene**	1,12	cis-Ocimene	1,76
Limonene	0,19	trans-Ocimene	2,03
β-Phellandrene	0,25	3-Octanone	0,92
γ-Terpinene	4,69	*1-Hexyl acetate*	0,54
***p*-Cymene**	3,87	α-Terpinolene	0,40
***1*-Octen-3-ol**	0,19	Octen-1-ol, acetate	0,34
Linalool	5,93	Hexyl butyrate	0,39
Linalyl acetate	0,26	Camphor	6,66
Terpinen-4-ol	0,81	Linalool	43,33
β-Caryophyllene	0,98	Linalyl acetate	19,82
Borneol	1,19	Lavandulyl acetate	1,91
β-Bisabolene	1,76	*β*-Caryophyllene	0,63
Caryophyllene oxide	0,22	Cryptone	0,42
Spathulenol	0,18	α-Terpineol	3,73
Thymol	1,52	Borneol	2,38

Carvacrol	73,78	Germacrene-D	0,25
Tanımlanamayan	0,22	Neryl acetate	0,98
		Geranyl acetate	1,79
		β-Citronellol	0,59
		Nerol	0,89
		Geraniol	2,18
		α-Bisabolol	0,84

Kekik ve lavanta suda yağ emülsiyonu (EW) formülasyonları uygulamalarının ve maruziyet sürelerinin (24, 48 ve 72 saat) *Meloidogyne incognita* ikinci dönem larvalarının (J2) ölüm oranları üzerindeki etkileri istatistiksel olarak önemli bulunmuştur (P<0,05). Uygulamaların nematisidal etkinliği hem kullanılan uçucu yağ türüne hem de maruziyet süresine bağlı olarak belirgin farklılık göstermiştir (Çizelge 2). Formülasyonlar arasında kekik uçucu yağı formülasyonu, tüm maruziyet sürelerinde lavantaya ve kontrole kıyasla istatistiksel olarak üstün bir nematisidal aktivite sergilemiştir. En yüksek J2 mortalitesi kekik formülasyonu uygulamasında 72 saat sonunda (%89) elde edilirken, aynı uçucu yağ 24 ve 48 saatlik maruziyetlerde de sırasıyla %78 ve %86 gibi yüksek ölüm oranları sağlamıştır. Aynı uygulamada 24. saat ile 48. ve 72. saat değerleri arasındaki farklılık istatistiksel olarak önemli bulunurken, 48. ve 72. saatler arasındaki farkın önemsiz olması, kekik uçucu yağının nematisidal etkisinin büyük ölçüde ilk 48 saat içerisinde ortaya çıktığını göstermektedir. Lavanta uçucu yağı formülasyonu ise kekik uygulamasına kıyasla daha ılımlı bir etki göstermiş, ancak 24, 48 ve 72. saatlerde sırasıyla %21, %33 ve %51 etki ile zamana bağlı olarak düzenli ve istatistiksel olarak anlamlı (P<0,05) bir mortalite artışı sergilemiştir. Lavanta uygulamasında üç değerlendirme zamanı arasındaki farklılıkların istatistiksel olarak önemli olması, nematisidal etkinin zamanla kademeli olarak arttığını göstermektedir.

Çizelge 2. Kekik ve lavanta aktif maddeli preparatların *Meloidogyne incognita* ikinci dönem larvalarına karşı tek doz 2000 ppm (2 µL mL^{-1}) kontakt etki sonuçları

Etmen	Uçucu yağ	% Ölüm±StDev		
		24h	48h	72h
Meloidogyne incognita	Kekik	77,7±0,3Ab	86,0±0,3Aa	89,2±0,5Aa
	Lavanta	21,0±0,2Bc	33,2±0,6Bb	50,9±1,1Ba
	Kontrol	0.0±0,0Cb	0.0±0,2Cab	0.4±0,6Ca

Uçucu yağların etkinlikleri aynı değerlendirme zamanları açısından karşılaştırıldığında, kekik uygulamasının lavanta uygulamasından tüm dönemlerde istatistiksel olarak daha yüksek ölüm oranı oluşturduğu görülmüştür (P<0,05). Nitekim 24. saatte kekik uygulamasında belirlenen %78'lik ölüm oranı, lavanta uygulamasında belirlenen %21'lık değerin yaklaşık 3,7 katı iken, 72. saatte bu fark %89'a karşı %51 olarak gerçekleşmiştir. Bu sonuçlar, çalışmada kullanılan koşullar altında kekik formülasyonunun *M. incognita* J2'lerine karşı lavanta formülasyonundan daha yüksek ve daha hızlı bir nematisidal etkiye sahip olduğunu ortaya koymaktadır. Tüm değerlendirme periyotlarında negatif kontrol grubundaki doğal ölüm oranları ihmal edilebilir düzeyde kalmış ve her üç zaman diliminde de uçucu yağ uygulamalarından istatistiksel olarak belirgin şekilde ayrılmıştır.

Çalışmada kullanılan uçucu yağların kimyasal bileşimleri dikkate alındığında, kekik uçucu yağında carvacrolün %73,78 ile açık ara baskın bileşen olması, bu yağın *M. incognita* J2'leri üzerindeki yüksek nematisidal aktivitesinin olası açıklamalarından biri olarak değerlendirilebilir. Buna karşılık lavanta uçucu yağında linalool (%43,33) ve linalyl acetate (%19,82) başlıca bileşenleri oluşturmuştur. Elde edilen kimyasal kompozisyon verileri, test edilen emülsiyonların *M. incognita* J2'leri üzerindeki nematisidal etkinlik farklılıklarını doğrudan açıklamaktadır. *O. onites* uçucu yağının gerek 24 saat gibi erken bir sürede (%77,7) gerekse 72 saat sonunda (%89,2) sergilediği üstün mortalite düzeyi, yağın bünyesindeki yüksek karvakrol içeriği (%73,78) ve fenolik yapısı ile ilişkilidir. Karvakrol, serbest hidroksil (-OH) grubu ve lipofilik karakteri sayesinde nematod kütikulasını ve hücre zarlarını hızla penetre ederek zar permeabilitesini bozar; iyon dengesizliğine, asetilkolinesteraz (AChE) inhibisyonuna ve sinir iletiminin felce uğramasına yol açar (Andrés vd., 2012; Barreto, 2025; Sarri vd., 2024; Trailović vd., 2021). Ayrıca karvakrolün biyosentez öncülleri olan p-simen (%3,87) ve γ-terpinen (%4,69) ile timolün (%1,52) karvakrol ile etkileşerek kontakt toksisiteyi etkilediği bilinmektedir; nitekim p-simenin karvakrol ile sinerjik etkileşimi nematisidal aktivite için kritik görülmekte (Sarri vd., 2024), timolün

diğer terpenoidlerle sinerjik etkisi ise kütikular penetrasyonun artmasıyla açıklanmaktadır (Tak ve Isman, 2017). Bununla birlikte karvakrol ile γ-terpinen ve o-simen ikili kombinasyonlarının *Meloidogyne* türlerine karşı azalmış etkinlik gösterebildiği de rapor edilmiştir (Sarri vd., 2024).

L. intermedia emülsiyonunda ise mortalitenin zamana bağlı olarak kademeli bir artış göstermesi (72 saatte %51), yağın ana bileşenleri olan linalool ve linalil asetatın doğasıyla uyumludur. Tersiyer alkol ve ester formundaki bu monoterpenoidler nematodlar üzerinde toksik ve davranış bozucu etkilere sahip olmakla birlikte, fenolik monoterpenler (karvakrol/timol) kadar agresif bir membran parçalayıcı veya hızlı knockdown etkisi oluşturmamaktadır. Dolayısıyla iki uçucu yağın farklı kimyasal profilleri, gözlenen nematisidal etkinlik ve etki hızındaki farklılıklara katkıda bulunmuş olabilir. Bununla birlikte, uçucu yağların biyolojik aktivitelerinin yalnızca baskın tek bir bileşenle açıklanması uygun olmayıp, diğer bileşenlerin ve bunlar arasındaki olası additif veya sinerjistik etkileşimlerin de etkili olabileceği dikkate alınmalıdır (Andrés vd., 2012; Sarri vd., 2024). Genel olarak değerlendirildiğinde, her iki uçucu yağ da *M. incognita* J2'leri üzerinde zamana bağlı nematisidal etki göstermiş olmakla birlikte, kekik uçucu yağı daha yüksek ve daha hızlı bir ölüm etkisi oluşturmuştur. Özellikle kekik uygulamasında 48. saatten sonra ölüm oranındaki artışın sınırlı kalması, etkinin erken dönemde büyük ölçüde gerçekleştiğini; lavanta uygulamasında ise 72. saate kadar belirgin bir artışın devam etmesi, bu uçucu yağın daha yavaş gelişen bir nematisidal etki gösterdiğini düşündürmektedir. Sonuç olarak, formülasyonların aktif bileşen profilleri, yüksek fenolik içerikli *O. onites* EW formülasyonunun *M. incognita* mücadelesinde hızlı ve kalıcı etki sağlayan bir biyopestisit adayı olduğunu doğrulamaktadır.

TEŞEKKÜR

Bu çalışma, Ankara Zirai Mücadele Merkez Araştırma Enstitüsü Müdürlüğü tarafından desteklenen TAGEM/BSAD/Ü/20/A2/P7/2842 nolu ve "Biyopestisit Formülasyon Araştırmaları" isimli projeden üretilmiştir

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ÇEMEN BİTKİSİNİN GENETİK ÇEŞİTLİLİKLERİNİN BELİRLENMESİ AMACIYLA YAPILAN MOLEKÜLER MARKER ÇALIŞMALARI

MOLECULAR MARKER STUDIES CONDUCTED TO DETERMINE THE GENETIC DIVERSITY OF FENUGREEK

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ÖZET

Çemen (*Trigonella foenum-graecum* L.), özellikle sağlık açısından faydalı bileşenleri ve gıda sanayiindeki kullanımı ile önemli bir bitkidir. Besin değerinin yüksek olması ve geleneksel tıpta çeşitli hastalıkların tedavisinde kullanılabilirliği nedeniyle büyük bir ekonomik değeri vardır. Çemen bitkisinin kalitesi, verimliliği ve hastalık dirençliliği gibi özellikleri genetik çeşitliliğe bağlıdır ve bu çeşitliliğin belirlenmesi, ıslah çalışmalarının başarı oranını arttırmaktadır.

Genetik çeşitliliğin değerlendirilmesinde klasik fenotipik analizlerin yanı sıra, son yıllarda moleküler marker kullanılarak yapılan çalışmalar daha hassas ve doğru sonuçlar elde edilmesini sağlamıştır. Moleküler marker teknikleri, çemen bitkisinin genetik yapısını daha derinlemesine incelemeyi mümkün kılmakta ve bu sayede farklı popülasyonlar arasında genetik farklılıkların tespit edilmesine olanak tanımaktadır. Bu çalışmada, çemen bitkisinin genetik çeşitliliğini belirlemek amacıyla yapılan moleküler marker çalışmalarına dair güncel bulgulara yer verilmiştir.

Anahtar Kelimeler: Çemen, DNA, Genetik Çeşitlilik, Islah, Moleküler Marker

ABSTRACT

Fenugreek (*Trigonella foenum-graecum* L.) is a significant plant, particularly due to its health-promoting components and its applications in the food industry. It holds substantial economic value owing to its high nutritional value and its potential use in traditional medicine for treating various diseases. Traits such as quality, yield, and disease resistance in fenugreek depend on genetic diversity, and determining this diversity enhances the success rate of breeding programs.

In evaluating genetic diversity, alongside traditional phenotypic analyses, studies utilizing molecular markers in recent years have yielded more precise and accurate results. Molecular marker techniques enable a deeper examination of the genetic structure of fenugreek, thereby allowing the identification of genetic variations among different populations. This study presents recent findings on molecular marker studies conducted to determine the genetic diversity of fenugreek.

Keywords: Fenugreek, DNA, Genetic Diversity, Breeding, Molecular Mark

ÇEMEN BİTKİSİ NEDİR?

Çemen *Fabales* takımı, *Fabaceae* (Baklagiller) familyası, *Trigonella* cinsi içerisinde bulunan bir bitkidir. Türkiye'de kültürü yapılmakta olan türü *Trigonella foenum-graecum* L.'dur. Ülkemizde *Trigonella* türlerinin dağılışı şu şekildedir: Kayseri, Gaziantep, Adana, Konya, Hatay, Mersin, Mardin ve Şanlıurfa (Kan ve Mülayim, 2006).

Çemen, birçok farklı alanlarda kullanılmaktadır. Bilhassa gıda, tıp, eczacılık ve kozmetik gibi alanlarda yaygın olarak kullanımı bulunmaktadır. Çemen bitkisinin gerek tohumları gerekse vejetatif aksamı çok farklı amaçlar için kullanılmaktadır (Özçelik, 2017). Çemen bitkisi, çok farklı iklim koşullarına adapte olabilmesi ve ekolojik çeşitliliği ile tarımsal üretim açısından da önemli bir yer tutmaktadır.

Çemen bitkisi, kökeni Anadolu'ya dayanan ve geniş bir adaptasyon yeteneğine sahip bir kültür bitkisidir. Özellikle toprak isteği bakımından kanaatkâr olması ve çok farklı alanlarda kullanım potansiyeli bulunması, onu yüzyıllardır bu ekosistemde önemli bir kültür bitkisi haline getirmiştir. Ancak son yıllarda, diğer yarı kurak bölgelerde yetişen bitkilerde olduğu gibi, çemenin ekim alanlarında da belirgin bir daralma yaşanmıştır. Bu gerilemenin sebeplerinden biri, Anadolu'da mevcut olan genetik

zenginlikten tam anlamıyla faydalanılmamasıdır. Bu genetik kaynaklardan yeterince yararlanarak, verimli ve kaliteli yeni çeşitlerin ıslahı üzerinde yeterince çalışma yapılmamıştır (Beyzi ve ark., 2010).

ÇEMEN BİTKİSİNİN İKLİMLE İLGİSİ

Ilıman iklim bölgelerinde iyi gelişim gösteren ve kışlık olarak ekimi yapılan, kuraklığa ve yüksek sıcaklıklara dayanıklılığı yüksek olan çemen bitkisinin Türkiye'de yetiştiriciliği; sıcak iklim bölgelerinde kışın ya da erken ilkbaharda, soğuk iklim bölgelerinde ise yaz mevsiminde yapılmaktadır (Kevseroğlu ve Özyazıcı, 1997).

Çemen, iklim koşullarına duyarlı bir bitki olmasına rağmen, özellikle ılıman iklimlerde yetişebilen, kuraklığa dayanıklı bir türdür. Ilıman iklimlerde, yaz sıcaklıklarının 20-30°C arasında olduğu, nem oranının düşük olduğu bölgelerde daha iyi gelişir. Çemen, genellikle sıcak iklim koşullarını tercih eder, ancak don olaylarının görüldüğü bölgelerde bu bitkinin yetişmesi zordur. Yüksek sıcaklıklar ve düşük nem oranı, çemenin optimum büyüme koşullarını oluşturur.

Çemen bitkisi, suya dayanıklı olmakla birlikte fazla suya gereksinim duymaz. Yine de kurak iklimlerde de başarılı bir şekilde yetişebildiği için, su kaynaklarının sınırlı olduğu bölgelerde önemli bir tarımsal ürün haline gelmiştir. Ancak, çemenin verimi için yeterli yağış ve suyun bulunması önemlidir. Genellikle düşük nemli, orta düzeyde suya sahip topraklarda verimli sonuçlar elde edilebilir.

Genetik çeşitlilik, çemenin farklı iklimsel koşullara uyum sağlama yeteneğini doğrudan etkileyebilir. Bu nedenle, çemenin farklı iklim koşullarındaki genetik yapısını anlamak, verimlilik ve adaptasyon çalışmaları açısından oldukça önemlidir. Moleküler markerler, bu adaptasyon süreçlerinin daha iyi anlaşılmasını sağlayarak, çemenin farklı iklim koşullarında daha verimli ve dirençli çeşitlerinin geliştirilmesine yardımcı olur.

GENETİK ÇEŞİTLİLİK NEDİR?

Bitki genetik kaynakları, bir bitki türünün gen havuzundaki kalıtsal bilginin çeşitliliğini ve zenginliğini içeren önemli kaynaklardır. Bu kaynaklar, yerel çeşitler olarak bilinen köy popülasyonları, bunların yabani akrabaları, artık günümüzde kullanılmayan eski çeşitler ve genetik özellikleri net bir şekilde belirlenmiş hatlardan oluşur. Özellikle yaklaşık 10.000 yıl önce kültüre alınan yerel bitki çeşitlerinde gözlemlenen genetik çeşitlilik, farklı yerel koşullara uyum sağlama özelliklerini yansıtarak bu türlerin evrimsel potansiyellerinin korunması ve ıslah çalışmalarında kullanılabilmesi açısından büyük önem taşır. Değişen çevre koşullarına uyum sağlayabilmesi için bir bitki türünün genetik çeşitliliğe sahip olması gerekmektedir. Bitki genetik kaynakları, içerdiği genetik çeşitlilik sayesinde biyoteknoloji alanında büyük bir hızla ilerleme kaydedilmesine olanak tanımış ve üstün nitelikli bitki çeşitlerinin geliştirilmesi için gerekli olan hammaddeleri sağlamaktadır (Altındal ve Akgün, 2015).

Bitki genetik kaynakları, tarihsel süreçte gelişen biyoteknoloji ve tarımsal çalışmalar sayesinde çeşitli ıslah çalışmaları ile yeni çeşitlerin ortaya çıkmasına olanak tanımaktadır. Bu kaynaklar, sahip oldukları yüksek allelik çeşitlilik nedeniyle genetik çeşitlilik açısından zengin bir gen havuzuna sahiptir. Özellikle farklı coğrafi ve iklimsel koşullara uyum sağlayabilme özellikleri sayesinde, dünya genelinde yayılım gösteren yabani kaynaklar büyük bir değere sahiptir. Çok eski zamanlardan itibaren kültüre alınan ve korunmuş olan yerel çeşitler, yerel koşullara adaptasyonları ve evrimsel süreçleri sayesinde, genetik çeşitlilik açısından önemli bir potansiyel sunmaktadır (İlhan, 2017).

ÇEMEN BİTKİSİNDE MOLEKÜLER MARKER ÇALIŞMALARI

I. *Trigonella* L. Cinsine Ait Bazı Türler Arasındaki Taksonomik İlişkilerin RAPD-PCR Yöntemi ile Belirlenmesi

2018 yılında Harran Üniversitesi Fen Bilimleri Enstitüsü, Biyoloji Anabilim Dalı'nda yürütülen bir yüksek lisans çalışmasında, Türkiye florasında doğal olarak yetişen *Trigonella* L. cinsine ait *Bucerates* Boiss. ve *Foenum-graecum* Ser. seksiyonlarında yer alan bazı türlerin moleküler düzeydeki taksonomik ilişkileri araştırılmıştır.

Bu çalışmanın temel amacı, söz konusu seksiyonlara ait 49 örnek üzerinden, moleküler bir analiz yöntemi olan Rastgele Çoğaltılmış Polimorfik DNA-Polimeraz Zincir Reaksiyonu (RAPD-PCR) tekniği kullanılarak tür içi ve türler arası genetik akrabalık düzeylerinin ortaya konmasıdır. Moleküler analizler kapsamında 20 farklı RAPD primeri test edilmiş, bunlardan 13'ü başarılı amplifikasyon vermiştir. Bu

13 primer aracılığıyla toplam 222 bant elde edilmiş olup, bu bantların tamamı (%100) polimorfik özellik göstermiştir. Primer bazında değerlendirildiğinde en fazla bant 23 adetle OPP09 primeriyle, en az bant ise 13 adetle OPB08 primeriyle elde edilmiştir. Genetik benzerliklerin değerlendirilmesinde, UPGMA (Unweighted Pair Group Method with Arithmetic Mean) algoritması kullanılarak bir dendrogram oluşturulmuştur. Elde edilen dendrogramda, 49 örnek 6 ana grup altında sınıflandırılmıştır.
Bu çalışma, RAPD markör tekniğinin *Trigonella* türleri arasındaki filogenetik ilişkilerin ortaya konmasında ve tür içi genetik polimorfizmin değerlendirilmesinde etkili ve güvenilir bir moleküler araç olduğunu göstermektedir.

II. İran'a Ait Çemen (*Trigonella foenum-graecum* L.) Yerel Irklarının SRAP Belirteçleri ile Genetik Çeşitliliğinin Belirlenmesi

Çemen hem tıbbi hem de gıda amaçlı kullanımıyla uzun süredir değerlendirilen önemli kültür bitkilerinden biridir. Yerel ırklar arasındaki genetik çeşitliliğin belirlenmesi hem bu genetik kaynakların korunması hem de gelecekte yürütülecek ıslah çalışmaları açısından temel bir adım niteliğindedir. Bu araştırmada, İran'a özgü sekiz farklı çemen otu yerel ırkından elde edilen 88 birey, SRAP (Sequence-Related Amplified Polymorphism) markörleri kullanılarak genetik çeşitlilik ve popülasyon yapısı açısından analiz edilmiştir.
Çalışmada kullanılan altı SRAP primeri ile toplam 72 bant elde edilmiş, bunların 56'sı (%80,11) polimorfik olarak tespit edilmiştir. Genetik çeşitlilik parametreleri açısından değerlendirildiğinde, Hamadan yerel ırkı; polimorfik lokus oranı (%67,86), Nei'nin genetik çeşitlilik indeksi (0,24), etkili alel sayısı (1,40) ve Shannon bilgi indeksi (0,36) bakımından en düşük değerlere sahip olmuştur. Nei'nin genetik mesafe analizine göre en yüksek uzaklık Hamadan ile Yazd arasında (0,203), en yüksek benzerlik ise Mahallat ile Varamin genotipleri arasında (0,036) belirlenmiştir. Ayrıca, gen akışı değerleri incelendiğinde en yüksek gen akışı Mahallat ile Varamin ırkları arasında (Nm = 8,36), en düşük gen akışı ise Şiraz ile Hamadan arasında (Nm = 0,66) gözlenmiştir.
Popülasyon yapısına ilişkin analizler, İran'a ait çemen otu yerel ırkları arasında alel düzeyinde belirgin bir genetik karışımın varlığını ortaya koymuştur. Bununla birlikte, Mantel testi sonuçları, genetik farklılaşma ve gen akışı ile coğrafi mesafe arasında anlamlı bir korelasyon olmadığını göstermiştir. Elde edilen sonuçlar, SRAP tekniğinin çemen otu genetik çeşitliliğinin ve popülasyon yapısının belirlenmesinde etkili ve güvenilir bir moleküler araç olduğunu göstermektedir.

III. Hindistan'a Ait Çemen (*Trigonella foenum-graecum*) Çeşitlerinde RAPD ve AFLP Yöntemleri ile Genetik Çeşitliliğin Değerlendirilmesi

Çemen otu (*Trigonella foenum-graecum*), Fabaceae (Baklagiller) familyasına mensup, yaygın olarak baharat ve tıbbi amaçlarla kullanılan önemli bir bitki türüdür. Dünya genelinde çemen otu üretiminde lider konumda olan Hindistan, aynı zamanda en büyük ihracatçı ülkedir. Bu çalışmada, Hindistan'a özgü beş yaygın çemen otu çeşidinin genetik çeşitliliği, moleküler düzeyde iki farklı yöntem kullanılarak analiz edilmiştir.
Genetik varyasyonu değerlendirmek amacıyla önce RAPD (Random Amplified Polymorphic DNA) analizi uygulanmış, dokuz farklı primer aracılığıyla 200-5000 bp aralığında toplam 47 DNA bandı elde edilmiştir. Bu bantların ortalama polimorfizm oranı %62,4 olarak hesaplanmıştır. Primer başına düşen bant sayısı 3 (U407) ile 7 (OPB-15) arasında değişmiştir. Çalışmada ayrıca, floresanla işaretlenmiş Amplified Fragment Length Polymorphism (AFLP) yöntemi de kullanılmıştır. Bu yöntemde 17 farklı primer kombinasyonu ile 50-538 bp aralığında toplam 669 bant amplifiye edilmiştir. Elde edilen bant sayısı, kullanılan primer kombinasyonuna göre 21 ile 60 arasında değişiklik göstermiştir. Nei'nin (1973) genetik çeşitlilik hesaplama yöntemine göre, tüm lokuslar üzerinden ortalama genetik çeşitlilik RAPD belirteçlerinde %23,83, AFLP belirteçlerinde ise %2,1 olarak belirlenmiştir. Toplamda 25 adet AFLP belirteci yalnızca belirli çeşitlere özgü bulunmuştur. Çeşitler arası genetik ilişkilerin ortaya konulabilmesi amacıyla, Nei'nin genetik mesafe katsayısı temel alınarak UPGMA (Unweighted Pair Group Method with Arithmetic Mean) algoritması ile filogenetik ağaçlar oluşturulmuştur. Her iki moleküler analiz sonucunda da Gujarat Methi-1 (GM-1) ve Gujarat Methi-2 (GM-2) çeşitlerinin aynı grupta yer aldığı ve diğer çeşitlere kıyasla birbirlerine daha yakın genetik ilişki sergilediği gözlemlenmiştir.

Sonuç olarak, RAPD belirteçlerinin çemen otu çeşitleri arasında AFLP'ye kıyasla daha yüksek düzeyde polimorfizm ortaya koyduğu ve genetik çeşitliliği daha ayrıntılı şekilde yansıttığı görülmüştür. Ancak, AFLP tekniği tekrarlanabilirlik ve güvenilirlik açısından RAPD'ye göre daha üstün bulunmuştur.

IV. *Trigonella foenum-graecum* L. Erişimleri Arasındaki Genetik Çeşitliliğin Morfometrik Özellikler ve ISSR Belirteçleri ile Değerlendirilmesi

Bu çalışma, Ulusal Bitki Genetik Kaynakları Bürosu (NBPGR), Yeni Delhi'de koruma altındaki *Trigonella* türlerinin karakterizasyonuna zemin oluşturmak amacıyla gerçekleştirilmiş ön nitelikte bir çalışmadır. Farklı ekocoğrafik bölgelerden toplanan 49 *Trigonella foenum-graecum* L. erişimi ve bir *T. corniculata* L. erişimi (dış grup olarak) genetik ilişkiler açısından değerlendirilmiştir. Çalışmada 19 morfometrik karakter ve 186 ISSR (inter-simple sequence repeat) belirteci kullanılmıştır. Erişimler; Hindistan'ın Andhra Pradesh, Himachal Pradesh, Jammu ve Keşmir, Madhya Pradesh, Uttar Pradesh, Uttarakhand, Rajasthan, Gujarat, Manipur ve Bihar eyaletlerinden toplanmış, ayrıca Eritre kökenli bir erişim de çalışmaya dahil edilmiştir. Elde edilen veriler doğrultusunda, 12'si nitel, 7'si nicel olmak üzere toplam 19 morfometrik özellik incelenmiş; birincil dal sayısı ve koza başına tohum sayısı dışındaki tüm kantitatif karakterlerde erişimler arasında anlamlı varyasyon gözlenmiştir. Shannon-Wiener Çeşitlilik İndeksi, tüm nicel karakterlerde belirgin bir çeşitlilik düzeyine işaret etmiştir. Morfometrik verilere dayalı kümeleme analizinde erişimler, yaklaşık %65 benzerlik düzeyinde iki ana gruba ayrılmıştır.

ISSR analizleri için başlangıçta 100 primer taranmış; bunlardan yalnızca 21 primer polimorfik bulunarak analizlerde kullanılmıştır. Bu primerlerle toplam 186 DNA bantı elde edilmiş ve bunların %92,4'ü polimorfik olarak belirlenmiştir. ISSR verilerine dayalı kümeleme sonucunda 47 erişim, yaklaşık %65 benzerlik düzeyinde aynı grupta toplanmıştır. Morfometrik ve ISSR verileri arasındaki ilişki zayıf düzeyde bulunmuş (Mantel testi, $r = 0.096$), ancak bazı coğrafi kökenli örneklerde her iki veri seti de benzer sonuçlar üretmiştir. Ayrıca, pasaport bilgisi bulunmayan bazı erişimlerin filogenetik yerleri, elde edilen veriler ışığında tahmin edilebilmiştir. Sonuçlar, ISSR belirteçlerinin morfometrik verilerle birlikte kullanıldığında, *Trigonella* erişimleri arasındaki genetik çeşitliliğin daha bütüncül şekilde değerlendirilebileceğini ortaya koymuştur.

SONUÇ

Çemenin genetik çeşitliliğini artırmak ve tarımsal verimliliğini iyileştirmek amacıyla yapılan moleküler marker çalışmaları, çemenin ıslahı için önemli bir araçtır. Yapılan araştırmalar, çemenin farklı coğrafi bölgelerindeki genetik varyasyonları ortaya koymakta ve verimlilik, hastalık direnci gibi tarımsal özelliklerin geliştirilmesi için gerekli genetik bilgilere ulaşılmasını sağlamaktadır. RAPD, AFLP, SSR, SNP, ISSR ve QTL gibi moleküler marker teknikleri, çemenin genetik çeşitliliğini incelemek ve verimliliğini artırmak için etkili bir şekilde kullanılmaktadır. Ayrıca, bu çalışmalar, çemenin genetik haritasının çıkarılmasında ve dayanıklı çeşitlerin geliştirilmesinde önemli katkılar sunmaktadır.

Çemen üzerinde yapılan moleküler marker çalışmalarının geleceği, genetik haritalama, genetik modifikasyon ve genomik seleksiyon gibi ileri düzey tekniklerle daha da ileriye taşınabilir. Genetik çeşitliliğin daha ayrıntılı bir şekilde belirlenmesi, çemenin daha verimli ve dayanıklı çeşitlerinin geliştirilmesine olanak tanıyacaktır. Ayrıca, çemenin çevresel streslere karşı dayanıklılığının artırılması ve hastalıklara karşı dirençli çeşitlerin elde edilmesi, tarımsal üretim için büyük bir önem taşımaktadır.

Gelecekte, yeni nesil DNA dizileme teknolojilerinin (NGS) ve biyoinformatik araçlarının kullanımıyla çemen bitkisinin genomu daha ayrıntılı bir şekilde analiz edilebilecek ve bu sayede genetik varyasyonlar daha hassas bir şekilde belirlenebilecektir. Ayrıca, çemenin metabolik yolları ve biyokimyasal özellikleri üzerine yapılan araştırmalar, çemenin tıbbi faydalarını daha iyi anlamamıza yardımcı olacaktır.

Sonuç olarak, moleküler markerlar, çemen bitkisinin ıslahında büyük bir potansiyele sahiptir ve bu tekniklerin gelişen biyoteknolojik uygulamaları ile çemenin genetik temelleri daha sağlam bir şekilde ortaya konulacaktır. Bu sayede, tarımsal verimliliği artırılmış, hastalıklara karşı daha dirençli ve çevresel streslere karşı daha dayanıklı çemen çeşitleri geliştirilmesi mümkün olacaktır.

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TÜRKİYE TARIMINDA BAKLAGİL VE BUĞDAYGİL YEM BİTKİLERİNİN ÖNEMİ, KULLANIM ALANLARI VE KALİTE KRİTERLERİ

THE IMPORTANCE, USAGE AREAS, AND QUALITY CRITERIA OF LEGUME AND GRASS FORAGE CROPS IN TURKISH AGRICULTURE

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ÖZET
Türkiye tarımında ve hayvancılık sektöründe karşılaşılan en temel sorunların başında, kaliteli ve ucuz kaba yem açığı gelmektedir. Baklagil ve buğdaygil yem bitkileri, yüksek besin değerleri, toprak verimliliğine ve ekim nöbetine katkıları ile ulusal tarım stratejilerinde kritik bir yere sahiptir. Baklagil yem bitkileri yüksek protein içerikleri ve toprağa biyolojik azot bağlama kapasiteleriyle ön plana çıkarken; buğdaygil yem bitkileri yüksek kuru madde verimleri, sindirilebilirlikleri ve enerji değerleriyle rasyon dengesini tamamlamaktadır. Bu bildiride, Türkiye'de yem bitkileri tarımındaki güncel durumu ele almak, sektörde karşılaşılan temel eksiklikleri değerlendirmek ve bu doğrultuda çözüm yolları ortaya koymak amaçlanmıştır. Bu amaç doğrultusunda, son dönemde gerçekleştirilen araştırmalar taranarak kapsamlı bir derleme sunulmuştur.
Anahtar Kelimeler: Baklagil Yem Bitkileri, Buğdaygil Yem Bitkileri, Kullanım Alanları, Kalite Kriterleri

ABSTRACT
One of the most fundamental problems encountered in Turkish agriculture and livestock sector is the deficit of high-quality and low-cost roughage. Legume and grass forage crops hold a critical position in national agricultural strategies due to their high nutritional values, as well as their contributions to soil fertility and crop rotation. While legume forage crops stand out with their high protein content and biological nitrogen fixation capacity in the soil, grass forage crops complement the ration balance with their high dry matter yields, digestibility, and energy values.
This paper aims to address the current situation of forage crop farming in Türkiye, evaluate the main deficiencies encountered in the sector, and propose solutions accordingly. In line with this objective, recent research was reviewed to present a comprehensive compilation.
Keywords: Legume Forage Crops, Grass Forage Crops, Areas of Usage, Quality Criteria

GİRİŞ
Beslenme, insanoğlunun yaşamını sürdürebilmesi ve biyolojik varlığını sağlıklı bir şekilde devam ettirebilmesi için en temel gereksinimlerden biridir. Bu hayati gereksinim doğrudan hayvansal ve bitkisel kaynaklı gıdalarla karşılanmakta, buna bağlı olarak dünya genelinde artan nüfusla birlikte her gün yüksek miktarlarda besin maddesi tüketilmektedir. İnsan beslenmesinde kritik bir role sahip olan hayvansal proteinlerin üretimi ise doğrudan hayvancılık sektörünün besleme girdilerine dayanmaktadır. Bu bağlamda buğdaygil ve baklagil yem bitkileri yetiştiriciliği, gerek bitkisel üretimin çeşitlendirilmesi gerekse hayvancılık sektörünün sürdürülebilir bir yapıya kavuşturulması açısından stratejik bir önem taşımaktadır (MEB, 2012). Yem bitkileri üretimi; bir yandan hayvancılığın en büyük gider kalemini oluşturan yem maliyetlerini düşürürken, diğer yandan tarımsal ekosistemlerin korunmasına, toprak verimliliğinin artırılmasına ve biyoçeşitliliğin desteklenmesine çok yönlü katkılar sunmaktadır.
Türkiye tarımında ve hayvancılık sektöründe karşılaşılan en temel yapısal ve kronik sorunların başında, kaliteli ve ucuz kaba yem açığı gelmektedir. Hayvansal üretimin sürdürülebilirliği, verimliliği ve işletme kârlılığı; rasyonun protein, enerji, lif ve mineral dengesini sağlayan kaliteli kaba yem kaynaklarının kesintisiz, standartlara uygun ve ekonomik biçimde temin edilmesine doğrudan bağlıdır. Ancak ülkemizdeki mevcut kaba yem üretim potansiyeli ve çayır-mera alanlarının mevcut verim seviyesi,

toplam hayvan varlığının fizyolojik besin maddesi gereksinimini karşılamakta yetersiz kalmaktadır. Kaliteli kaba yem arzındaki bu yetersizlik, yetiştiricileri pahalı kesif (yoğun) yem kullanımına yöneltmekte; bu durum işletmelerin toplam üretim maliyetlerini aşırı seviyelere çıkararak hayvancılık sektörünün rekabet gücünü ve karlılığını ciddi şekilde olumsuz etkilemektedir.

Söz konusu kaba yem açığının kapatılmasında, yem maliyetlerinin optimize edilmesinde ve dengeli rasyon modellerinin kurulmasında tek yıllık baklagil ve buğdaygil yem bitkileri son derece stratejik bir yere sahiptir. Baklagil yem bitkileri; yüksek ham protein içerikleri, zengin mineral bileşimleri, iştahla tüketilebilir lezzetlilikleri ve köklerinde bulunan *Rhizobium* simbiyotik bakterileri vasıtasıyla atmosferik azotu toprağa bağlama yetenekleriyle ön plana çıkmaktadır. Biyolojik azot fiksasyonu sağlayan bu mekanizma, hem hayvan beslemede yüksek kaliteli protein kaynağı oluşturmakta hem de kimyasal gübre kullanımını azaltarak toprak verimliliği, toprak yapısının iyileştirilmesi ve ekim nöbeti sistemleri açısından büyük ekolojik avantajlar sunmaktadır. Buğdaygil yem bitkileri ise yüksek kuru madde verimleri, yüksek sindirilebilir enerji değerleri ve lezzetlilikleriyle rasyonun lif ile enerji ihtiyacını dengeli bir şekilde karşılamakta, aynı zamanda saçak kök sistemleri sayesinde toprağı erozyona karşı korumaktadır.

Tüm bu özelliklerinin yanı sıra baklagiller; kırsal alanda istihdama sağladıkları doğrudan katkı, yüksek katma değerli ürün altyapılarıyla sundukları ihracat potansiyelleri, farklı ürün desenleriyle ekim nöbetine kolay entegre olabilme kabiliyetleri ve nadas alanlarının daraltılmasındaki kilit rolleri nedeniyle tarımsal ekonomide vazgeçilmez bir konuma sahiptir. Kurak ve yarı kurak iklim kuşaklarında toprağın nadasa bırakılması yerine tek yıllık baklagil yem bitkileriyle değerlendirilmesi, toprak organo-mineral dengesini yeniden yapılandırırken yem üretiminde süreklilik sağlamaktadır. Besin değeri açısından son derece zengin olan bu bitki grubu, toprağın fiziksel ve kimyasal yapısını iyileştirirken hayvancılık sektörünün dönemsel yem ihtiyacını karşılayarak ulusal ölçekte hem üretim hem de tüketim dengesi açısından hayati bir işlev üstlenmektedir.

BAKLAGİL VE BUĞDAYGİL YEM BİTKİLERİNİN ÖNEMİ VE KULLANIM ALANLARI

Baklagil yem bitkileri, sahip oldukları üstün nitelikler nedeniyle dünya genelinde ve ulusal tarım sistemlerinde son derece geniş bir kullanım alanına sahiptir. Bu bitkiler, biçim zamanına ve türüne bağlı olarak kuru otlarında ve tanelerinde %40'a varan yüksek ham protein oranlarıyla öne çıkmaktadır (Açıkgöz, 2001). Hayvan gelişimi açısından kritik önem taşıyan mineral maddeler, vitaminler ve büyüme teşvik edici unsurlarca zengin bir yapı sunan baklagiller, otlatma veya ot üretimi amacıyla buğdaygillerle karışım halinde yetiştirildiklerinde karışımın toplam ot verimini ve protein kalitesini belirgin şekilde artırmaktadır (Yolcu & Tan, 2009).

Besleme değerinin yanı sıra baklagil yem bitkileri, ekolojik ve toprağı koruyucu işlevleriyle de sürdürülebilir tarımın temelini oluşturmaktadır. Köklerinde barındırdıkları *Rhizobium* yumrucuk bakterileri vasıtasıyla havanın serbest azotunu toprağa bağlayan bu türler, toprağa bıraktıkları bol kök artıkları ve yeşil gübreleme uygulamaları sayesinde organik maddece fakir toprakların yapısını iyileştirmektedir (Açıkgöz, 2001; MEB, 2012). Ayrıca yatık gelişen, köksaplı ve sülüklü baklagil türleri erozyon kontrolünde etkili rol oynarken; korunga, yonca ve taş yoncası gibi türler kendilerine özgü tat, koku ve aromaya sahip bal üretimine katkı sağlayan değerli nektar (balözü) kaynakları olarak kabul edilmektedir.

Buğdaygil yem bitkileri, yüksek adaptasyon kabiliyetleri, geniş ekim alanları ve hayvan beslemedeki temel rolüyle tarımsal üretimin vazgeçilmez unsurlarından biridir. Bu bitkiler; yüksek kuru madde verimleri, sindirilebilir enerji değerleri ve lezzetlilikleriyle rasyonun lif (NDF ve ADF) ile enerji gereksinimini karşılamakta son derece etkindir (Açıkgöz, 2001; MEB, 2012). Baklagillerle kıyaslandığında daha yüksek karbonhidrat ve nişasta içeriğine sahip olan buğdaygiller, ruminant hayvanlarda işkembe (rumen) metabolizmasının sağlıklı işlemesi ve sindirim düzeninin korunması açısından kritik bir denge oluşturmaktadır (Yolcu & Tan, 2009). Bunun yanı sıra, mısır ve sorgum gibi türler yüksek verimli silaj yapımına mükemmel uyum sağlarken, çok yıllık türler mera ve çayır alanlarının ana ve taşıyıcı vegetasyonunu meydana getirmektedir.

Besleyici niteliklerinin ötesinde buğdaygil yem bitkileri, toprağın fiziksel yapısını koruyan ve erozyon riskini azaltan güçlü ekolojik işlevlere sahiptir. Saçak kök sistemleri sayesinde toprağı sıkıca kavrayarak su ve rüzgâr erozyonunu önlemede oldukça başarılıdırlar. Ayrıca ekim nöbeti sistemlerinde toprağın havalanmasını sağlama, organik madde birikimini artırma ve toprak strüktürünü iyileştirme

özellikleriyle öne çıkarlar. Baklagil yem bitkileri ile karışım halinde ekildiklerinde ise hem karışımın toplam ot verimini yükseltmekte hem de tek başına baklagil otlatmasında görülebilen şişme (timpani) riskini ortadan kaldırarak güvenli bir otlatma zemini sunmaktadır (Gökkuş,1994).Besleme değeri açısından değerlendirildiğinde baklagil yem bitkileri, buğdaygillere kıyasla daha yüksek kalitede yem biyokütlesi sağlamaktadır. Bu durum, baklagil türlerinin bünyesinde daha düşük oranda lif içermesinden ve buna bağlı olarak hayvanlar tarafından iştahla ve yüksek miktarlarda tüketilebilmesinden (yüksek yem alımı) kaynaklanmaktadır. Baklagil ve buğdaygil yem bitkilerinin karışım halinde yetiştirilmesinin (yalın ekime tercih edilmesinin) temel gerekçesi de elde edilen yemin toplam kalitesini ve besin dengesini yükseltmektir. Nitekim baklagillerin ham protein bakımından zengin yapısı ile buğdaygillerin yüksek sindirilebilir karbonhidrat ve enerji içeriği bir araya geldiğinde, hayvanların fizyolojik ihtiyaçlarına uygun dengeli bir rasyon yapısı elde edilmektedir (Yolcu & Tan, 2008; Budak & Budak, 2014).

BAKLAGİL VE BUĞDAYGİL YEM BİTKİLERİNİN KALİTE KRİTERLERİ

Yem kalitesi; hayvansal verimlilik, yemin besleme değeri ve işletme kârlılığı üzerinde doğrudan belirleyici bir role sahiptir. Kavramsal olarak geniş bir içeriğe sahip olan yem kalitesi; yemin içerdiği besin maddeleri, enerji seviyesi, ham protein oranı ve niteliği, sindirilebilirlik derecesi, lif yapısı ile mineral ve vitamin bileşiminin yanı sıra doğrudan hayvan performansıyla ilişkilendirilmektedir. Yemin besleyici niteliği çoğunlukla bünyesindeki Toplam Sindirilebilir Besin (TSB) miktarı ve ham protein düzeyi ile açıklanmaktadır. Ancak pratik yetiştiricilikte yem kalitesi, yalnızca kimyasal besin içeriğini değil, aynı zamanda yemin hayvan tarafından iştahla tüketilebilirliğini (yem alımını) de kapsamaktadır. Bu doğrultuda, özellikle mera ve otlatma koşullarında hayvanların canlı ağırlık artışı, süt verimi ve genel üretim performansı, tüketilen yemin kalitesini gösteren en temel pratik göstergelerdir (Budak & Budak, 2014).

Yem bitkilerinin besleme değeri ve nihai kalitesi, birbiriyle etkileşim halinde olan pek çok faktör tarafından şekillenmektedir. Bu faktörler arasında yem bitkisinin türü, biçim/hasat anındaki fenolojik olgunluk evresi, uygulanan hasat yöntemi ile depolama ve muhafaza teknikleri birincil derecede belirleyici unsurlar olarak öne çıkmaktadır. Bununla birlikte, yetiştiricilik yapılan toprağın verimlilik düzeyi ve gübreleme rejimleri ile vejetasyon dönemi boyunca etkili olan sıcaklık koşulları ve iklimsel dalgalanmalar, yem kalitesini doğrudan ve dolaylı olarak etkileyen ikincil derecedeki önemli faktörleri oluşturmaktadır (Budak & Budak, 2014).

Biçim zamanının doğru belirlenmesi, yemin kimyasal bileşimi ve hayvan tarafından değerlendirilebilirliği üzerinde hayati bir etkiye sahiptir. Vejetatif gelişmenin ileri aşamalarında bitkiler olgunlaştıkça, bünyelerindeki hücre içeriği oranı azalırken, destek dokularını oluşturan hücre duvarı bileşenlerinin miktarı artış göstermektedir. Özellikle buğdaygillerde başaklanma ve tohum bağlama dönemine girildikçe, baklagillerde ise çiçeklenme oranının artmasıyla birlikte gövde ve sap dokularında odunlaşma, yani lignifilasyon süreci hız kazanmaktadır. Lignin maddesinin selüloz ve hemiselüloz ile karmaşık bağlar kurması, işkembedeki mikroorganizmaların lifli dokuları parçalama kapasitesini sınırlandırmakta ve yem maddesinin sindirilebilirliğini düşürmektedir. Sindirilebilirliği azalan yemin işkembede kalış süresi uzamakta, bu durum hayvanın birim zamandaki kuru madde tüketimini baskılayarak nihai hayvansal verimin düşmesine yol açmaktadır. Dolayısıyla, baklagillerde erken tomurcuklanma ile ilk çiçeklenme arasındaki dönem, buğdaygillerde ise gebeleşme ve başak çıkarma başlangıcı, besin maddesi birikimi ile lif kalitesi arasındaki dengenin en ideal olduğu biçim zamanlarıdır.

Laboratuvar analizlerinde kaba yem kalitesini derecelendirmek amacıyla kullanılan enstürmantal ölçütler, yemlerin rasyonlardaki kullanım oranlarını doğrudan belirlemektedir. Bu analizlerin başında gelen Nötr Deterjanda Çözünmeyen Lif (NDF) oranı yemin hacimselliğini ve hayvanın yem tüketim sınırını ifade ederken, Asit Deterjanda Çözünmeyen Lif (ADF) oranı ise yemin sindirilebilirlik derecesini doğrudan yansıtmaktadır. Yüksek NDF ve ADF değerleri yemin besleyici değerini düşürmekte, buna karşılık Nispi Yem Değeri (NYD) ve Nispi Yem Kalitesi (NYK) gibi kombine indekslerin gerilemesine neden olmaktadır. Ayrıca protein niteliği değerlendirilirken sadece toplam ham protein miktarı değil, bu proteinin işkembede yıkımlanma derecesi ve bağırsaklara ulaşan by-pass protein oranı da dikkate alınmalıdır. Baklagillerde yapraklar, saplara kıyasla çok daha yüksek oranda

protein ve mineral içerdiğinden, biçim ve kurutma esnasında yaprak dökülmelerinin önlenmesi, yemin besleme değerinin korunması açısından kritik bir zorunluluktur.

Hasat sonrası uygulanan koruma ve depolama yöntemleri de yem kalitesinin nihai seviyesini doğrudan etkileyen faktörler arasındadır. Otun tarlada kurutulması sürecinde meydana gelen mekanik yaprak kayıpları, solunum kayıpları ve olası yağışlar nedeniyle besin maddelerinin yıkanması, kaba yemin enerji ve protein değerinde önemli azalmalar meydana getirebilmektedir. Diğer taraftan, silaj yapımı gibi fermantasyona dayalı muhafaza yöntemlerinde, ortamın anaerobik koşullara ulaştırılması ve laktik asit bakterilerinin hızlı dominasyonu yem kalitesini doğrudan belirlemektedir. Buğdaygiller kolay fermente olabilir şeker içerikleri sayesinde silajlaşmaya son derece uygun bir yapı sunarken, baklagillerin yüksek tamponlama kapasitesi ve düşük şeker içerikleri silaj yapımında katkı maddesi kullanımını veya buğdaygillerle karışık ekim biçiminde değerlendirilmelerini gerekli kılmaktadır. Sonuç olarak, baklagil ve buğdaygil yem bitkilerinde yüksek yem kalitesine ulaşılması; bitki türünün doğru seçilmesi, en uygun fenolojik dönemde biçimin gerçekleştirilmesi, toprak ve iklim koşullarının iyi yönetilmesi ve depolama süreçlerinde besin maddesi kayıplarının en aza indirilmesiyle mümkündür.

SONUÇ

Türkiye'de hayvancılık sektörünün sürdürülebilirliği ve ekonomik olarak devamlılığı açısından kaliteli, yeterli ve ekonomik kaba yem üretiminin artırılması büyük önem taşımaktadır. Baklagil ve buğdaygil yem bitkileri, sahip oldukları farklı ancak birbirini tamamlayan besin özellikleri sayesinde hayvanların ihtiyaç duyduğu protein, enerji ve lif kaynaklarının karşılanmasında önemli bir potansiyele sahiptir. Baklagillerin yüksek ham protein içeriği ve atmosferik azotu toprağa bağlama özellikleri, buğdaygillerin ise yüksek kuru madde ve enerji verimleri ile birleştiğinde hem hayvan besleme hem de sürdürülebilir tarımsal üretim açısından önemli avantajlar ortaya çıkmaktadır.

Yem bitkilerinin yalnızca hayvan besleme açısından değil, toprak verimliliğinin korunması, organik madde miktarının artırılması, erozyonun azaltılması ve ekim nöbeti sistemlerinin sürdürülebilirliğinin sağlanması açısından da değerlendirilmesi gerekmektedir. Özellikle baklagil ve buğdaygil yem bitkilerinin uygun oranlarda karışım halinde yetiştirilmesi, elde edilen yemin besin madde dengesini ve kullanım değerini artırabilmektedir. Bu nedenle yem bitkileri üretiminde yalnızca yüksek verim hedeflenmemeli, aynı zamanda elde edilen yemin besleme değeri ve kalite özellikleri de üretim planlamasının temel unsurlarından biri olarak dikkate alınmalıdır.

Sonuç olarak, Türkiye'de kaba yem açığının azaltılması ve hayvansal üretimde yem maliyetlerinin düşürülmesi için yem bitkileri üretiminin nicelik ve nitelik bakımından geliştirilmesi gerekmektedir. Bunun için bölgeye uygun baklagil ve buğdaygil tür ve çeşitlerinin belirlenmesi, uygun yetiştirme tekniklerinin yaygınlaştırılması, karışık ekim sistemlerinin geliştirilmesi ve hasat ile muhafaza süreçlerinde yem kalitesini koruyacak uygulamaların benimsenmesi önem taşımaktadır. Böylece yem bitkileri üretiminin artırılması yanında, hayvancılığın verimliliğine ve tarımsal üretimin sürdürülebilirliğine de önemli katkılar sağlanabilecektir.

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THE IMPACT OF CBRT POLICY RATE CYCLES AFTER THE 2008 GLOBAL CRISIS ON THE REAL AND FINANCIAL SECTORS: IMPULSE-RESPONSE ANALYSIS

2008 KRİZİ SONRASI TCMB POLİTİKA FAİZİ DÖNGÜLERİNİN REEL SEKTÖR VE FİNANSAL SEKTÖRE ETKİLERİ: ETKİ-TEPKİ ANALİZİ

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Abstract
Central banks prioritize their primary objective in determining policy interest rates. Accordingly, while the primary objective of the Central Bank of the Republic of Türkiye (CBRT) is to ensure price stability, the recession and sudden influx of hot money caused by the 2008 crisis led it to also prioritize financial stability and to implement an expansionary monetary policy through gradual interest rate reductions. Following the easing of the effects of the 2008 crisis, as part of the normalization process in global monetary policies, the CBRT adopted a tight monetary policy with gradual interest rate increases. Following the Covid-19 pandemic, the CBRT adopted a cautious approach and took expansionary steps, beginning with interest rate cuts. As a result, the aim of these measures is to improve the financial sector alongside the recovery of the real sector. In conclusion, the aim of these practices is to improve the financial sector alongside the recovery in the real sector. The purpose of this study is to present evidence regarding the impact of the cycles in the CBRT policy interest rate on the real and financial sectors in the Turkish economy, from the period when the 2008 crisis began to have an impact to the present day, including the Covid-19 pandemic. Accordingly, the effects of changes in the one-week repo interest rate on the industrial production index, employment level, unemployment rate, commercial loan interest rates, and the basket exchange rate during the period 2008:M9-2026:M6 were examined using impulse-response functions. The main findings of the analysis, which externally included the monetary policy practices indicated by the 2008 crisis and the Covid-19 pandemic in the model, are as follows: (i) interest rate decisions, especially those aimed at mitigating the negative effects of shocks, do not meet expectations in economic activity and the labor market; (ii) the publicly announced policy interest rate creates a signal perception in market interest rates and exchange rate developments; (iii) it is noticeable that real sector indicators should be taken into account in the main trend of the monetary stance in general. Therefore, it is understood that the CBRT will contribute to sustainable growth and increased social welfare with its monetary policy strategy that supports financial stability. Indeed, it is important here to evaluate the limitations of financial conditions, which are primarily represented by interest rates and exchange rates and have a significant impact on economic activity.
Keywords: CBRT Policy Rate, Real Sector, Financial Sector, Impulse-Response Functions

Özet
Politika faiz oranının belirlenmesinde merkez bankalarının temel hedefi önceliklidir. Buna göre, Türkiye Cumhuriyet Merkez Bankası (TCMB)'nın temel hedefi fiyat istikrarını sağlamak iken 2008 krizinin yol açtığı durgunluk ve ani sıcak para hareketliliği sonucu finansal istikrarı da gündemine almış ve kademeli faiz indirimleriyle genişletici para politikasını uygulamaya başlamıştır. 2008 krizinin etkilerinin hafiflemesinin ardından küresel para politikalarında normalleşme süreci kapsamında TCMB kademeli faiz artışlarıyla sıkı para politikasını benimsemiştir. Covid-19 pandemisi sonrasında ise TCMB temkinli yaklaşımla genişletici yönde adımlar atmış; faiz indirimlerine başlamıştır. Sonuç olarak, söz konusu uygulamalarla ulaşılmak istenen reel sektördeki toparlanmanın yanında finansal sektörün iyileştirilmesidir. Bu çalışmanın amacı, Türkiye ekonomisinde 2008 krizinin etkili olmaya başladığı dönemden Covid-19 pandemisinin de dahil olduğu günümüze kadar olan süreçte TCMB politika faizindeki döngülerin reel ve finansal sektöre yansımalarına ilişkin kanıtlar sunmaktır. Bu doğrultuda, 2008:M9-2026:M6 döneminde 1 hafta vadeli repo faiz oranındaki değişikliklerin sanayi üretim endeksi, istihdam düzeyi, işsizlik oranı, ticari kredi faiz oranları ve sepet kur üzerindeki etkileri etki-tepki fonksiyonlarıyla incelenmiştir. 2008 krizi ve Covid-19 pandemisi ile bu süreçlerin işaret ettiği para politikası uygulamalarının modele dışsal olarak dahil edildiği analizin başlıca bulguları şunlardır: (i)

özellikle şokların olumsuz etkilerini zayıflatmaya yönelik alınan faiz kararları ekonomik faaliyetler ve işgücü piyasasında beklentileri karşılamamaktadır; (ii) kamuoyuna ilan edilen politika faiz oranı, piyasa faiz oranları ve döviz kuru gelişmelerinde sinyal algısı oluşturmaktadır; (iii) genel olarak parasal duruşun ana eğiliminde reel sektör göstergelerinin dikkate alınması gerektiği göze çarpmaktadır. Dolayısıyla, TCMB'nin finansal istikrarı destekleyici para politikası stratejisiyle sürdürülebilir büyüme ve toplumsal refah artışına katkı sağlayacağı anlaşılmaktadır. Nitekim, burada özellikle ekonomik faaliyetler üzerinde etkili olan; faiz oranı ve döviz kuru ağırlıklı temsil edilen finansal koşulların sınırlılıklarının değerlendirilmesi önemlidir.

Anahtar Kelimeler: TCMB Politika Faizi, Reel Sektör, Finansal Sektör, Etki-Tepki Fonksiyonları

BIBLIOMETRIC ANALYSIS OF THE CONCEPT OF DIGITAL LEADERSHIP USING R STUDIO

DİJİTAL LİDERLİK KAVRAMININ R STUDİO İLE BİBLİYOMETRİK ANALİZİ

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Abstract
Action plans aligned with digital transformation are being designed to ensure organizational survival in a competitive landscape driven by digital leadership. With technological advancements, the effective management of processes can be complemented by the innovative ideas and strategies of digital leaders. The need for digital leaders is steadily increasing to facilitate a successful transition into the digitalizing world, and digital leadership is becoming increasingly prominent in this era of digitalization. This study aims to conduct a bibliometric analysis of research on digital leadership published in journals indexed in the Web of Science databases. The study covers publications from the last eight years and performs both performance analysis and science mapping of the articles. The "bibliometrix" package for R software was utilized for the bibliometric analysis. A sample consisting of 1452 studies was analyzed. The results reveal a significant increase in research on digital leadership and identify the United States as the most productive country in this field across all metrics. The study highlights trending topics that emerged from the bibliometric analysis findings, such as leadership, digital transformation, and performance. Furthermore, Administrative Sciences, Cogent Business & Management, and the Journal of Business Research are identified as the most prolific journals in the digital leadership literature. This study serves as a guide for researchers to understand the evolution of digital leadership over time and identify topics requiring further attention; it also provides direction on grasping and applying performance analysis and science mapping methods in any research field. The study is expected to contribute to researchers, the industry, and organizations by offering a comprehensive framework for digital leadership management.
Keywords: Digital leadership, Leadership, Bibliometric analysis

Özet
Dijital liderlikle rekabet ortamında kurumların ayakta kalmaları dijital dönüşüme uygun hareket planları tasarlanmaktadır. Teknolojinin ilerlemesiyle süreçlerin etkin şekilde yönetilmesi dijital liderlerin yenilikçi fikirleri ve stratejileriyle tamamlanabilmektedir. Dijitalleşen dünyaya başarılı bir şekilde geçiş yapmak için dijital liderlere olan ihtiyaç giderek artmakta ve dijitalleşme çağında dijital liderliğin dijitalleşme çağında daha da ön plana çıkmaktadır. Bu çalışma, Web of Science veri tabanlarındaki dergilerden dijital liderlik üzerine bibliyometrik bir analiz yapmayı amaçlamaktadır. Çalışma, son 8 yıllık yayınları kapsamakta ve makalelerin performans analizi ve bilim haritalama analizini gerçekleştirmektedir. Bu çalışmada, bibliyometrik analiz için R yazılımının “bibliometrix” paketi kullanılmıştır. Toplam 1452 çalışmadan oluşan bir örneklem analiz edilmiştir. Sonuçlar, dijital liderlik alanındaki araştırmaların 2026 yılında önemli ölçüde arttığını ve Amerika Birleşik Devletleri’nin bu alanda her açıdan en üretken ülke olduğunu ortaya koymuştur. Bu çalışma, bibliyometrik analiz bulguları sonucunda öne çıkan liderlik, dijital dönüşüm ve performans gibi trend konuları vurgulamaktadır. Ayrıca, Administrative Sciences, Cogent Business/Management, Journal of Business Research dergileri dijital liderlik literatüründe en çok yayın yapan dergilerdir. Bu çalışma, araştırmacılar için dijital liderliğin zaman içinde nasıl evrildiğini ve alanda daha fazla dikkat gerektiren konuları anlamak için bir rehber görevi görecek ve araştırmacılara herhangi bir araştırma alanında performans analizi ve bilimsel haritalama yöntemlerini kavrayıp uygulama noktasında yol gösterici olacaktır. Çalışmanın gerek araştırmacılara gerek endüstriye gerekse kurumlara dijital liderlik yönetimi ile ilgili genel bir çerçeve sunarak katkı sağlaması beklenmektedir
Anahtar kelimeler: Dijital liderlik, Liderlik, Bibliyometrik analiz

İŞLETMELERDE MAKİNE ÖĞRENMESİNİN R PROGRAMI İLE ANALİZİ

ANALYSIS OF MACHINE LEARNING IN BUSINESSES USING THE R PROGRAM

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ABSTRACT

Machine learning enables the updating of an algorithm's architectural structure to enhance model efficiency based on results obtained by testing various action parameters—specifically for scenarios requiring action based on conditions inherent in traditional algorithmic structures. Machine learning algorithms are increasingly preferred for modeling customer interest in goods and services, factors influencing demand, potential production yields, the impact of quality and price fluctuations on actions, and the likelihood of parameter changes translating into specific actions. Machine learning methods allow for the design of algorithmic structures that help firms maximize revenue, maintain and improve customer satisfaction, eliminate supply-side losses, sustain competitiveness, and enhance operational efficiency. This study aims to conduct a bibliometric analysis of research on machine learning in business contexts, drawing from journals indexed in the Web of Science databases. It covers publications from the last decade and performs both performance and science mapping analyses. The "bibliometrix" package for R software was utilized for the bibliometric analysis, examining a sample of 413 studies. The results reveal a significant increase in machine learning research and identify the United States as the most prolific country in this field across all metrics. The study highlights key journals—such as Technological Forecasting and Social Change, Journal of Business Research, and IEEE Transactions on Engineering Management—as the leading publishers on this topic, while also emphasizing trending subjects such as big data, analytics, and systems. This study serves as a guide for researchers to understand the evolution of machine learning and identify areas requiring further attention; it also provides direction on grasping and applying performance analysis and scientific mapping methods within any research field.

Keywords: Machine Learning, Businesses, Bibliometric analysis

ÖZET

Makine öğrenmesi, geleneksel algoritma yapısında var olan koşula göre aksiyon alma durumları için aksiyon parametrelerinin algoritmalar tarafından farklı değişkenler ile denenerek, elde edilen sonuçlara göre modelin verimliliğini arttırabilecek şekilde mimari yapısının güncellenmesine olanak sağlamaktadır. Müşterilerin mal ve hizmet taleplerine olan ilgisini, talebi etkileyen faktörleri, üreticilerin ürünlerinde elde edecekleri verimi, ürüne dair kalite, fiyat hareketlerinin aksiyona etkisini ve parametrelerdeki değişimlerin aksiyona dönüşme ihtimallerini en iyi şekilde modelleyebilme çabalarında makine öğrenmesi algoritmaları da tercih edilmektedir. Firmaların ciro üretimlerinde başarılarını maksimize etmelerinde, müşteri memnuniyetlerini karşılama noktasındaki verimlerini muhafaza etme ve arttırma çabalarında, mal ve hizmet arzlarındaki kayıpların bertaraf edilmelerinde, rekabetçi yanlarını korumada, faaliyet verimlerinin iyileştirilmesinde tercih edilebilecek algoritma yapıları makine öğrenmesi metotları ile kurgulanabilmektedir. Bu çalışma, Web of Science veri tabanlarındaki dergilerden işletmelerde makine öğrenmesi üzerine bibliyometrik bir analiz yapmayı amaçlamaktadır. Çalışma, son 10 yıllık yayınları kapsamakta ve makalelerin performans analizi ve bilim haritalama analizini gerçekleştirmektedir. Bu çalışmada, bibliyometrik analiz için R yazılımının “bibliometrix” paketi kullanılmıştır. Toplam 413 çalışmadan oluşan bir örneklem analiz edilmiştir. Sonuçlar, makine öğrenmesi konusundaki araştırmaların 2026 yılında önemli ölçüde arttığını ve Amerika birleşik Devletlerinin bu alanda her açıdan en üretken ülke olduğunu ortaya koymuştur. bibliyometrik analiz bulguları sonucunda konu ile ilgili en çok yayın yapan Technological Forecasting And Social Change, Journal of Business Research, Ieee Transactions on Engineering Management dergileri yer almaktadır. Big data, analytics ve system gibi trend konular vurgulanmaktadır. Bu çalışma, araştırmacılar için makine öğrenmesinin zaman içinde nasıl evrildiğini ve alanda daha fazla dikkat gerektiren konuları anlamak için bir rehber görevi görecek ve araştırmacılara herhangi bir

araştırma alanında performans analizi ve bilimsel haritalama yöntemlerini kavrayıp uygulama noktasında yol gösterici olacaktır.

Anahtar kelimeler: Makine Öğrenmesi, İşletmeler, Bibliyometrik analiz

FROM HIGH-TECH TO HIGH-TOUCH: ANALYZING THE ADVERTISING MESSAGES OF LEADING BANKS IN TURKIYE FROM AN H2H MARKETING PERSPECTIVE

HIGH-TECH'TEN HIGH-TOUCH'A: TÜRKİYE'DEKİ LİDER BANKALARIN REKLAM MESAJLARININ H2H PAZARLAMA PERSPEKTİFİNDEN ÇÖZÜMLENMESİ

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ÖZET
Pazarlamanın dönüşüm yolculuğunun son durağı olan İnsandan İnsana Pazarlama (H2H Marketing) hakkında sahaya dönük uygulama ve ampirik çalışma bulguları son derece kısıtlıdır. Bu çalışmanın amacı, aktif büyüklük bakımından Türkiye'nin ilk beş bankasının son bir yılda yayımladığı reklam filmlerinde H2H pazarlama felsefesinin izlerini incelemektir. Bu amaçla bankaların kurumsal YouTube kanallarından erişilen 172 reklam filmi; tasarım odaklı düşünme, hizmet baskın mantık ve dijitalleşme boyutları çerçevesinde yönlendirilmiş nitel içerik analiziyle çözümlenmiştir. Bulgular, reklam mesajlarında en fazla empatik dil, ardından değer ortak yaratımı ve dijitalleşme boyutlarının yer aldığını göstermektedir. Sonuçlar, bankaların tasarım odaklı empatik bir yapıya sahip iletişimi güçlü biçimde benimsediğini, hizmet baskın mantık kapsamında değerin ortaklaşa yaratıldığı ve tüketicinin sürece daha çok dahil edildiği bir hizmet sunum sürecini tasarlamakta ve sunmakta yeterli seviyeye ulaşılamadığını ve dijitalleşmeden elde edilen faydaların daha görünür hale getirilememesi ile birlikte dijitalleşme nedeniyle yaşanabilecek soğukluğu ve veri güvenliği riskini ortadan kaldırmaya yönelik mesaj içeriklerinde yetersiz kalındığını göstermektedir.
Anahtar kelimeler: *İnsandan İnsana Pazarlama, Bankacılık Sektörü, Reklam, Nitel İçerik Analizi, Dijitalleşme*

ABSTRACT
While empirical findings and field applications regarding Human-to-Human (H2H) Marketing —the destination of marketing's evolutionary journey—remain extremely limited, this study aims to examine the traces of the H2H marketing philosophy in the commercial films released over the past year by Turkey's top five banks in terms of asset size. To this end, 172 commercial films retrieved from the banks' official YouTube channels were analyzed through directed qualitative content analysis within the framework of design thinking, service-dominant logic, and digitalization dimensions. The findings indicate that empathetic language appears most frequently in commercial messages, followed by the dimensions of value co-creation and digitalization. The results demonstrate that while banks have strongly adopted design-oriented empathetic communication, they have not yet reached an adequate level in designing and delivering a service provision process where value is co-created and consumers are more actively involved within the scope of service-dominant logic. Furthermore, the findings reveal a shortcoming in making the benefits of digitalization more visible, as well as an insufficiency in message contents aimed at eliminating the sense of detachment and data security risks associated with digitalization.
Keywords: *Human-to-Human Marketing, Banking Sector, Advertising, Qualitative Content Analysis, Digitalization*

GİRİŞ
Son yirmi yılda pazarlama teorisi, işlemsel ve ürün odaklı modellerden, duygusal bağ, ortak değer yaratımı ve deneyim temelli değere dayanan yaklaşımlara doğru önemli bir paradigma dönüşümü geçirmiştir (Al-Darraji, Movaghar, Safari ve Hosseini, 2025).

Pazarlama disiplinine yönelik giderek derinleşen güven sorunu bu dönüşümün önemli tetikleyicilerinden biridir. Nitekim aşırı kâr odaklı bazı pazarlamacıların etik dışı uygulamaları, pazarlamanın çalışanlar ve müşteriler nezdindeki algısını olumsuz etkilemiş olup bu durum pazarlamanın yalan, aldatma, sahtekârlık ve manipülasyon gibi kavramlarla özdeşleştirilmesine yol açmıştır. Sahte pazar araştırması sonuçları gibi kamuoyu skandalları da bu olumsuz imajı iyice derinleştirmiştir (Kotler, Pfoertsch ve Sponholz, 2021).

İşletmelerin, hükümetlerin, sivil toplum kuruluşlarının ve medyanın karşı karşıya bulunduğu bu güven krizini aşabilmek amacıyla yeni bir pazarlama paradigmasına duyulan ihtiyaç giderek artmıştır. Bu noktada Kotler vd.'ne (2021) göre pazarlamanın hayatta kalabilmesi için anlamlı değer önermeleri yaratmanın özüne dönmesi gerekmektedir ve bu da İnsandan İnsana Pazarlama Modeli (Human-to-Human Marketing, H2H) sayesinde gerçekleştirilebilecektir. H2H pazarlama modeli, Tasarım Odaklı Düşünme, Hizmet Baskın Mantık ve Dijitalleşme'den oluşan üçlü bir yapı üzerinden hareket ederek işletmeler ve markaların kendilerini yeniden konumlandırmalarına rehberlik etmektedir. Bu sayede kaybedilen güvenin yeniden kazanılabilmesi mümkün hale gelebilmektedir. B2B ve B2C paradigmalarının aksine H2H yaklaşımı, müşteriyi yalnızca bir tüketici olarak görmeyip sosyal, duygusal ve kültürel bağlamı içerisinde yer alan bütüncül bir birey olarak ele almaktadır (Kotler vd., 2021).

Bu kapsamda bu çalışma ile, aktif büyüklük bakımından Türkiye'nin ilk beş bankasını oluşturan T.C. Ziraat Bankası A.Ş., Türkiye Vakıflar Bankası T.A.O., Türkiye İş Bankası A.Ş., Türkiye Halk Bankası A.Ş. ve Türkiye Garanti Bankası A.Ş.'ye ait reklam mesajlarında H2H pazarlama modeline dair izlerin sürülmesi amaçlanmaktadır.

1. H2H (İnsandan İnsana) Pazarlama Yaklaşımı: Kavramsal Temeller

Son yıllarda dijital dönüşümün markalar ile tüketiciler arasındaki etkileşim biçimlerini derinden değiştirmesi, işletmeden işletmeye (B2B) ve işletmeden tüketiciye (B2C) gibi geleneksel pazarlama yaklaşımlarının, gerçek dünyadaki müşteri ilişkilerinin duygusal, ilişkisel ve kültürel karmaşıklığını açıklamakta yetersiz kalmasına yol açmıştır (Al-Darraji vd., 2025). Chatbotlar, algoritmik kişiselleştirme ve otomatik yanıt sistemleri gibi teknolojik uygulamaların yaygınlaşması, operasyonel verimlilik sağlamakla birlikte müşteri ilişkilerinin insani boyutunu da zayıflatmış olup bu durum tüketicilerin pazarlamacılara yönelik güveninin aşınmasına ve markalardan her zamankinden daha fazla özgünlük, empati ve şeffaflık talep etmesine zemin hazırlamıştır (Babay, 2025). Yaşanılan teknolojik patlama, tüketim dinamiklerini ve markaların müşterilerle etkileşim kurma biçimlerini derinden dönüştürmekle birlikte işletmeler için önemli operasyonel verimlilik kazanımları sunmuş olsa da müşteri ilişkilerinin insani boyutunu zayıflatarak işletmelerin çözmesi gereken bir paradoks yaratmıştır. H2H pazarlama modeli, teknolojik yeniliğin faydalarını göz ardı etmeden insanı yeniden stratejinin merkezine yerleştirmeyi öneren temel bir stratejik yanıt olarak bu paradoksal gerginlikten ortaya çıkmaktadır (Babay, 2025). Pazarlamanın giderek daha veri odaklı, algoritmik ve dijital bir arka plan üzerinden yürüdüğü günümüzde hedef kitlede oluşan bu rahatsızlığı aşabilmek amacıyla, tasarım odaklı düşünmeyi, hizmet baskın mantık yaklaşımını ve dijitalleşme süreçlerini bütünleştiren bir model olarak önerilen H2H pazarlama modeli ilk olarak (Kotler vd., 2021) tarafından yeni bir pazarlama perspektifi ve zihinsel dönüşüm modeli olarak tasarlanmıştır (Rivera, 2023).

H2H pazarlama modeli, müşteri merkezliliği insan merkezliliğe genişleterek pazarlamayı yalnızca ticari bir işlemler bütünü olarak değil, güven, empati ve ortak değer yaratımına dayalı etik ve insani bir etkileşim biçimi olarak yeniden tanımlamaktadır (Kotler vd., 2021). İnsan değerini, özgünlüğü, empatiyi, duygusal karşılıklılığı ve ortak değer yaratımını merkeze alan bu yaklaşım, insanlaştırılmamış etkileşimlerin sınırlılıklarına ve dijital evrende yer alan postmodern tüketicilerin yeni beklentilerine stratejik bir yanıt niteliği taşımaktadır (Pfoertsch, 2024). Bu kapsamda H2H pazarlama, tüketici yerine insanı önceleyen bir anlayışla karakterize edilmekte olup bu yaklaşımda odak noktası müşterinin rolü değil, onun duyguları, beklentileri ve ihtiyaçları olan bir birey olarak varlığıdır (Babay, 2025).

H2H pazarlama modelinde (Kotler vd., 2021), Tasarım Odaklı Düşünme (Design Thinking), Hizmet Baskın Mantık (Service-Dominant Logic) ve Dijitalleşme (Digitalization) olmak üzere üç temel bileşeni bir araya getiren teorik bir çerçeve sunmaktadır.

1.1. Tasarım Odaklı Düşünme (Design Thinking):

İnsanları ilk sıraya koyan bir inovasyon stratejisi olan Tasarım Odaklı Düşünme'de, insanların gereksinim, davranış ve deneyimlerini anlamak kritik önem taşımaktadır. Bu kapsamda tüketicilerin

gerçek ihtiyaçlarını karşılayan ürünler geliştirmek amacıyla onlarla empatik konuşmalara yönelmek, H2H pazarlamanın özünde yer almaktadır (Roshid, Karim ve Waaje, 2024). Bu yaklaşım, şekil ve düzen gibi geleneksel kaygıların çok ötesine geçen, karmaşık sorunları çözmeye yönelik sistematik ve insan merkezli bir yöntemdir. Kullanıcı ihtiyaçları ve kullanıcı odaklı buluş bu sürecin merkezinde yer almaktadır (Kotler vd., 2021). Tasarım odaklı düşünme; anla, gözlem yap, bakış açısını tanımla, tasarla/fikir üret, prototip oluştur ve test et (*understand, observe, define point of view, ideate, prototype and test*) aşamalarından oluşmaktadır ve bu aşamalar yinelemeli (iterative) olarak devam eden bir süreç niteliği taşımaktadır (Kotler vd., 2021). Empatinin temel rol oynadığı tasarım odaklı düşünmeye, Dove markasının doğal güzelliği teşvik ettiği ve gerçekçi olmayan standartlara meydan okuduğu "Real Beauty" (Gerçek Güzellik) kampanyası örnek olarak verilebilir. Bu reklamda marka; farklı vücut yapılarına, yaşlara ve kökenlere sahip gerçek kadınları öne çıkarmayı ve şefkatli, kapsayıcı ve kendini kabule odaklanmış mesajlara ağırlık vermeyi tercih etmektedir (Babay, 2025).

1.2. Hizmet Baskın Mantık (Service Dominant Logic)

Hizmet Baskın Mantık, odağı ürünlerden hizmetlere kaydırarak ekonomik işlemlerin doğasını yeniden ele almaktadır. Vargo ve Lusch'un (2004) pazarlama için yeni bir baskın mantık olarak ortaya koyduğu hizmet baskın mantık yaklaşımı, doğası gereği ilişki odaklı bir mantığı benimsemekte, değerin ortak yaratımını (value co-creation) merkeze almakta ve pazarlama faaliyetlerinin ağ yapısı ve ardından ekosistem perspektifi çerçevesinde değerlendirilmesini önermektedir. H2H Pazarlama modeli de bu görüşü benimseyerek hizmet baskın mantığı kendi kavramsal temellerinden biri olarak kabul etmektedir (Kotler vd., 2021). Müşterilerle kurulan anlamlı bağlantılar ve onların hizmet yaratım ve sunum sürecine aktif katılımı bu yaklaşımın önemli bir ayağını oluşturmaktadır (Roshid vd., 2024). Bu anlayışta odak noktası üretici, kaynaklar veya ürün değil; aktörler arasındaki etkileşimler olup tüm aktörler hizmetin ortak üreticileri olarak görülmektedir. Örneğin LEGO Ideas, hayranlarını platformu aracılığıyla setler tasarlamaya ve bunlara oy vermeye teşvik etmektedir. Hayranlar yeni ürünler için fikirler ortaya atmakta ve yeterli oy alanlar, kutunun üzerinde yaratıcının adıyla birlikte resmi bir sürüm haline getirilmektedir. Marka, fikirleri yalnızca bir veri olarak kullanmamakta, yaratımın ardındaki bireyi tanımakta ve onun hayal gücünü, tutkusunu ve Lego evrenine duygusal katkısını kutlamaktadır (Babay, 2025).

1.3. Dijitalleşme (Digitalization)

İşletmeler için dijitalleşmenin asla göz ardı edilemeyeceği bir ortamda H2H modeli dijital dünya ile insani özellikleri birbirine entegre ederek tüketici deneyimini çok daha eşsiz bir noktaya çıkarmayı hedeflemektedir. Bu kapsamda, bireysel müşterinin tercih ve davranışlarına göre uyarlanmış mesajlar ve teklifler kullanan kişiselleştirilmiş pazarlama, H2H pazarlama uygulamasının ayrılmaz bir parçasını oluşturmaktadır (Roshid vd., 2024). Ancak kişiselleştirilmiş dijital deneyimlerin sürdürülebilirliği, tüketici verilerinin gizlilik, şeffaflık ve etik kullanım ilkeleri doğrultusunda yönetilmesine bağlıdır. Tüketicilerin verilerinin nasıl toplandığı ve hangi amaçlarla kullanıldığı konusunda açık biçimde bilgilendirilmesi, dijital etkileşimlerde güvenin oluşmasını ve marka–müşteri ilişkisinin güçlenmesini desteklemektedir (Bleier, Goldfarb ve Tucker, 2020). Bu kapsamda dijitalleşme ile birlikte diğer iki H2H boyutunun (tasarım odaklı düşünme ve hizmet baskın mantık) birlikte uygulandığı çarpıcı bir örnek Whole Foods Market olarak gösterilebilmektedir. Bu işletme, en başından itibaren sürekli olarak sağlıklı gıda çözümleri sunarak ve mevcut kamu gerekliliklerinin ötesinde kalite standartları oluşturarak bir Hizmet Baskın Mantığı izlemiştir. Tekliflerini ve prosedürlerini geliştirmek için Tasarım Odaklı Düşünmeyi uygulamaktadırlar. Çevrimiçi dağıtım ve dijital iletişim ise fiziksel ve dijital amaç mesajını senkronize etmek için stratejik olarak kullanılmaktadır (Kotler vd., 2021b).

1.4 *Bankacılık Sektöründe Dijitalleşme, Yapay Zekâ ve H2H Pazarlama İlişkisi*

Bankacılık sektörü, modern ekonomilerin işleyişinde kritik bir rol oynamakta ve son on yıllarda yapay zekâ gibi ileri teknolojilerle güçlendirilen dijital bankacılık hizmetlerinin yükselişiyle önemli dönüşümler geçirmektedir (Duarte, 2026). Bankacılıkta yapay zeka uygulamaları, hesap açma, para yatırma, fatura ödeme ve işlem hatırlatıcıları gibi düşük kullanım değerine sahip işlevlerden; banka hesapları hakkında gerçek zamanlı kişiselleştirilmiş tavsiyeler, yatırım portföyleri, emeklilik planlaması, borç konsolidasyonu ve sigorta planlaması gibi yüksek kullanım değerine sahip gelişmiş hizmetlere kadar geniş bir yelpazede sınıflandırılabilmektedir (Manser Payne, Dahl ve Peltier, 2021). Varlık yönetimi ve kredi değerlemesi gibi alanlarda da kullanılan yapay zekâ destekli robot danışmanlar, artık sınırlı insan müdahalesiyle müşterilerin satın alma karar süreçlerine yardımcı olarak müşteri

deneyiminin bir parçası hâline gelmiş (Ho ve Chow, 2024; Mostafa, 2025) ve bu süreçte bankalar ile müşteriler değer yaratımında birlikte hareket eden bir yapıya kavuşmuştur. Tam da bu noktada, H2H pazarlamanın bileşenlerini oluşturan tasarım odaklı düşünme ve dijitalleşme ile birlikte hizmet baskın mantık kapsamında değerin ortaklaşa yaratılması, bankacılık sektörüyle güçlü bir örtüşme sergilemektedir.

2. Metodoloji

Türkiye'nin aktif büyüklük açısından ilk beş bankasının reklam mesajlarında H2H yaklaşımının izlerini sürmeyi amaçlayan bu çalışmanın metodolojik tasarımı, H2H pazarlama modelinin 3 alt boyutu üzerine inşa edilmiş olup reklam filmlerinde bu boyutların varlığı incelenmiştir.

Tasarım Odaklı Düşünme (Empatik Dil): Reklam mesajlarında müşterinin postmodern kaygılarının, finansal dertlerinin ve duygularının ne ölçüde anlaşıldığına yönelik olarak insani ve samimi bir tonun varlığı.

Hizmet Baskın Mantık (Değerin Ortak Yaratımı): Teknolojinin veya bankacılık hizmetlerinin tek taraflı bir dayatmadan ziyade, müşteriyi sürecin aktif bir ortağı ve değerin oluşturulmasında önemli bir ortak olarak konumlandıran mesaj içerikleri.

Dijitalleşme: Tüketicilerin hayatlarını kolaylaştırabilmek adına teknoloji ve dijital imkânların seferber edildiği bir ortamda bu çabayı reklam mesajlarına yansıtabilmek. Bir diğer ifadeyle dijitalleşmeyi sadece işletmeye sağladığı maliyet avantajı nedeniyle kullanmak yerine hedef kitleye sağladığı avantajların çok daha önemli olduğuna yapılan vurgu ve dijital uygulamaların müşteri deneyim yolculuğunun zenginleştirilmesine sağladığı katkının ön plana çıkarılması.

2.1. Araştırmanın Deseni ve Yöntemi

Bu çalışmada, Türkiye'deki lider bankaların reklam mesajlarında H2H pazarlama modelinin ne ölçüde yer bulduğunu derinlemesine incelemek amacıyla nitel araştırma yaklaşımlarından yönlendirilmiş içerik analizi yöntemi benimsenmiştir. İçerik analizi, metin, ses veya görsel gibi iletişim materyallerinin belirli kodlar ve kategoriler çerçevesinde sistematik olarak çözümlenmesine, gizli ve açık anlamların organize edilmesine olanak tanıyan nesnel bir yöntemdir (Schreier, 2012). H2H pazarlama modelinin henüz olgunlaşmış ve genel kabul görmüş bir nicel ölçüm ölçeğinin bulunmaması, konunun ancak nitel desenli çalışmalar aracılığıyla incelenmesini mümkün kılmaktadır. Araştırmada, teorik çerçeveden hareketle önceden belirlenmiş kavramsal kategorilerin (tasarım odaklı düşünme/empatik dil, hizmet baskın mantık/değer ortak yaratımı, dijitalleşme/kolaylaştırıcı ve güven) reklam metinlerine uygulandığı yönlendirilmiş içerik analizi yaklaşımı kullanılmıştır. Yönlendirilmiş içerik analizinde, analiz süreci, başlangıç kodlarının oluşturulmasına rehberlik eden bir kuram veya ilgili araştırma bulguları temel alınarak yürütülmektedir (Hsieh ve Shannon, 2005).

2.2. Evren ve Örneklem

Araştırmanın evrenini, Türkiye'de faaliyet gösteren ve kitlesel iletişim araçlarında aktif olarak reklam veren bankacılık sektörü oluşturmaktadır. Araştırmanın örneklemi ise nitel araştırmalarda sıklıkla başvurulan amaçlı örnekleme yöntemlerinden ölçüt örnekleme tekniğiyle belirlenmiştir (Yıldırım ve Şimşek, 2016). Bu doğrultuda, Türkiye Bankalar Birliği (TBB) veya BDDK verilerine göre Türkiye'de faaliyet gösteren aktif büyüklük bakımından ilk beş içerisinde yer alan bankalar araştırmanın örneklemini oluşturmaktadır. Bu ölçüte göre örneklem olarak seçilen bankalar; T.C. Ziraat Bankası A.Ş., Türkiye Vakıflar Bankası T.A.O., Türkiye İş Bankası A.Ş., Türkiye Halk Bankası A.Ş. ve Türkiye Garanti Bankası A.Ş'den oluşmaktadır (TBB, 2026). Söz konusu bankaların kitle iletişim araçlarında 15.07.2025 ile 15.07.2026 tarihleri arasında yayınlanan reklam filmleri analize dahil edilmiştir.

2.3. Veri Toplama Süreci ve Analizi

Araştırmanın verileri, belirlenen 5 bankanın kurumsal YouTube kanalında yer alan reklam filmlerinin transkript edilmesi (ses, diyalog, dış ses ve ekrandaki metinlerin yazıya dökülmesi) yoluyla elde edilmiştir. Toplanan metinsel veriler analiz edilirken Miles ve Huberman (1994) tarafından önerilen üç aşamalı nitel veri analizi süreci (verilerin indirgenmesi/kodlanması, verilerin görselleştirilmesi/tablolaştırılması ve sonuç çıkarma/teyit etme) takip edilmiştir. Veri toplama sürecinde bankaların YouTube hesaplarında yayınlanan ve ulusal medya araçlarında reklam olarak yer almayan video paylaşımları (kariyer günü etkinlikleri, girişimcilik günü etkinlikleri, belirli bir alana ait uzmanla yapılan söyleşi vb.) analiz kapsamına dahil edilmemiştir. Böylelikle tüm toplumu hedef alan reklam içeriklerinin incelenebilmesine imkân sağlanmıştır. Yapılan değerlendirme sonucunda belirlenen

kıstaslara uygun toplam 172 reklam filmi analize dâhil edilmiş olup elde edilen verilerin banka bazlı dağılımı ve kodlama güvenirliği testleri Bulgular bölümünde detaylandırılmıştır.

3. Bulgular ve Tartışma

Reklam metinleri, sloganlar ve diyaloglardan oluşan veri seti, mekanik bir puanlama cetveline başvurulmaksızın, H2H pazarlama modelinin kuramsal çerçevesinden belirlenen üç temel alt boyut doğrultusunda çözümlenmiştir.

3.1. Tanımlayıcı İstatistikler ve Reklamların Bankalara Göre Dağılımı

Reklam filmlerinin bankalara göre dağılımı incelendiğinde; en yüksek paya %24,4 (42 adet reklam) ile Türkiye Garanti Bankası A.Ş ile Türkiye İş Bankası A.Ş'nin sahip olduğu görülmektedir. Bunu sırasıyla %23,2 (40 adet reklam) ile Türkiye Halk Bankası A.Ş., %15,7 (27 adet reklam) ile T.C. Ziraat Bankası A.Ş. ve %12,3 (21 adet reklam) ile Türkiye Vakıflar Bankası T.A.O. takip etmektedir. İncelenen 172 reklam filminin banka bazlı sayısal ve yüzdesel dağılımı Tablo 1'de detaylandırılmıştır.

Tablo 1. İncelenen Reklam Kampanyalarının Banka Bazında Dağılımı

Banka Adı	Reklam Sayısı (Frekans)	Yüzde (%)
Türkiye Garanti Bankası A.Ş.	**42**	**24.4**
Türkiye İş Bankası A.Ş.	**42**	**24,4**
Türkiye Halk Bankası A.Ş.	**40**	**23,2**
T.C. Ziraat Bankası A.Ş.	**27**	**15,7**
Türkiye Vakıflar Bankası T.A.O.	**21**	**12,3**
Toplam	**172**	**100**

3.2. Kodlayıcılar Arası Uyum Analizi (Cohen's Kappa)

Araştırmada nesnelliği, tutarlılığı ve metodolojik güvenirliği en üst düzeyde sağlamak amacıyla, veri setinin sınıflandırılmasında iki bağımsız kodlayıcı görev almıştır. Analiz sürecinde, incelenen 172 reklam filminin metinleri banka bazında kategorize edilerek bir veri matrisine (Excel) aktarılmış ve her reklam filminin karşısına H2H pazarlama modelinin 3 temel alt boyutu (Tasarım Odaklı Düşünme, Hizmet Baskın Mantık ve Dijitalleşme) birer analiz sütunu olarak eklenmiştir. Kodlayıcılar, analiz sürecinde reklam metinlerini derinlemesine okumakla birlikte dilsel bağlamın ve örtük anlamların daha iyi kavranabilmesi adına ilgili reklam videolarını da eş zamanlı olarak izlemişlerdir.

Sınıflandırma sürecinin ardından kodlayıcılar bir araya gelerek bağımsız kararlarını karşılaştırmıştır. Kodlayıcılar arası tutarlılığın istatistiksel geçerliliğini test etmek amacıyla, nitel içerik analizlerinde yaygın olarak kabul gören Cohen's Kappa (ƙ\kappa) uyum katsayısı kriterine başvurulmuştur. Literatürde Landis ve Koch (1977) tarafından önerilen Kappa katsayısını yorumlama ölçütlerine göre; 0 ile 0,2 hafif uyumu, 0,2 ile 0,4 adil/iyi uyumu, 0,4 ile 0,6 orta düzeyde uyumu, 0,6 ile 0,8 önemli uyumu, 0,8 ile 1,0 arası ise "neredeyse mükemmel uyumu" göstermektedir (Sun, 2011).

Çalışmanın odağını oluşturan üç temel H2H boyutu üzerindeki kodlamaların ilk analizi sonucunda, iki kodlayıcı arasındaki uyum düzeyi ƙ = 0,79 (önemli uyum) olarak hesaplanmıştır. İlk turda üzerinde fikir birliği sağlanamayan reklam filmleri, her iki kodlayıcı tarafından diğer kodlayıcının atadığı alt boyut çerçevesinde bireysel ve bağımsız olarak tekrar değerlendirilmiştir. Bu ikinci değerlendirme sonucunda uyum katsayısı ƙ = 0,87'ye yükselmiştir. Elde edilen Cohen's Kappa kriteri, kodlayıcılar arasında "neredeyse mükemmel uyum" olduğunu ortaya koymaktadır. Kodlama esnasında ortaya çıkan az sayıdaki fikir ayrılığı, araştırmacılar tarafından bir araya gelinerek H2H kuramsal çerçevesinin dinamikleri doğrultusunda yeniden tartışılmış ve tam uzlaşı ile karara bağlanarak nihai tablolara yansıtılmıştır.

İki kodlayıcının ortak sınıflandırması sonucunda elde edilen nihai bulgular, reklam mesajlarından yapılan doğrudan alıntılarla (slogan, motto ve diyaloglar) desteklenerek ve H2H pazarlama literatürüyle ilişkilendirilerek aşağıda üç ana başlık altında sunulmuştur.

3.3. H2H Pazarlama Boyutlarının Banka Bazında Güncel Frekansları

H2H pazarlama modelinin üç temel bileşeninin banka bazındaki frekans dağılımları hesaplanmış ve sonuçlar Tablo 2'de detaylandırılmıştır.

Tablo 2: H2H Pazarlama Boyutlarının Banka Bazında Frekans Dağılımı

Banka Adı	Toplam Reklam Sayısı	Tasarım Odaklı Düşünme	Hizmet Baskın Mantık	Dijitalleşme
Türkiye Garanti Bankası A.Ş.	42	40	18	15
Türkiye İş Bankası A.Ş.	42	35	28	9
Türkiye Halk Bankası A.Ş.	40	39	14	6
T.C. Ziraat Bankası A.Ş.	27	26	8	4
Türkiye Vakıflar Bankası T.A.O.	21	19	9	8
Toplam Mutabakat	172	159	77	42

Tablo 2 bütünsel olarak incelendiğinde, veri seti (172 reklam) üzerinde de en çok ağırlık verilen H2H boyutunun önemli bir farkla Tasarım Odaklı Düşünme / Empatik Dil (159 frekans) boyutu olduğu görülmektedir. Bu boyutu ikinci sırada Hizmet Baskın Mantık / Değerin Ortak Yaratımı (77 frekans) takip ederken, dijitalleşmenin getirdiği kolaylığın yanı sıra dijitalleşme nedeniyle oluşabilen algoritmik soğukluğu kırmayı, siber evrende insani bir duruş sergilemeyi ve güven oluşturmayı hedefleyen Dijitalleşme (42 frekans) boyutu ise en düşük frekansa sahip boyut olarak saptanmıştır.
Banka bazlı performanslara bakıldığında ise, Türkiye Garanti Bankası A.Ş., tasarım odaklı düşünme (40 frekans) ve dijitalleşme (15 frekans) boyutlarında en yüksek görünürlüğe ulaşırken, Türkiye İş Bankası A.Ş., hizmet baskın mantık (28 frekans) boyutunda rakiplerine kıyasla daha yoğun bir kurumsal konumlandırma sergilemiştir.

3.4. Bulguların Alt Boyutlara Göre Değerlendirilmesi ve Metinsel Alıntılar

3.4.1. Tasarım Odaklı Düşünme Kapsamında Reklamlarda "Empatik Dil" Boyutu

Tasarım odaklı düşünme, pazarlama odağını salt finansal işlemlerden koparark insanı sürecin merkezine alan, onun gündelik yaşam pratiklerini, duygusal dünyasını ve postmodern kaygılarını derin bir empatiyle ele alan stratejik bir yaklaşımdır. Analiz edilen transkriptlerdeki cümleler ve verilmek istenilen mesajlar incelendiğinde, bankaların karmaşık finansal ve operasyonel terimler yerine tüketiciyle duygu ortaklığı kuran insani bir dil inşa ettiği saptanmıştır. Diğer taraftan incelenen reklam mesajlarında, tüketicilerin sahip oldukları sorunların ve bankacılık hizmetlerinden nasıl bir beklenti içinde olunduğunun farkında olunduğu ve bu sorunlarla beklentilere yönelik çözümler için çabalandığının bankalar tarafından sıklıkla dile getirildiği tespit edilmiştir.
Örneğin T.C. Ziraat Bankası A.Ş.'nin reklam mesajında geçen *"….Prestij Dünyası sizi düşünüyor size de bu hayatın tadını çıkarmak kalıyor. Siz de bu ayrıcalıklı dünyanın bir parçası olmak için en prestijli kartı seçin yeni hayatınıza Merhaba deyin…."* vurgusu, doğrudan bankanın tüketicileri düşündüğünün açık bir ifadesidir.
Türkiye Garanti Bankası A.Ş'nin "Gençler Garanti BBVA Mobil'de toplandı!" temalı reklam filminde yer alan, *"…E genç olmak zaten yeterince karışık. En azından bankacılık işleri dağılmasın diye hepsini Garanti BBVA Genç'te topladık…"* ifadeleri, bankanın kendisini hedef kitlesinin yerine koyarak gerçek sorunlarının farkında olduğunu ve bu sorunların çözümüne yönelik teklifler oluşturduğunu güçlü bir şekilde vurgulayan empatik dile örnek oluşturmaktadır.
Türkiye Vakıflar Bankası T.A.O'nun milli takım sponsorluğu kapsamındaki "Bu Heyecan Bizim, Bu Çocuklar Bizim" reklamında yer alan "*Bu takım bizim, bu heyecan bizim, bu tutku bizim, bu sevgi bizim, bu inanç bizim, bu çocuklar bizim…"* vurgusu, bireysel finansal kaygıların ötesine geçerek toplumsal motivasyon, kolektif ruh ve ortak aidiyet duygularını yakalayan güçlü bir empatik dil örneği olarak değerlendirilmektedir.
Tasarım odaklı düşünme boyutuna dair bir diğer örnek ise, Türkiye Halk Bankası A.Ş.'nin "Halkbank 88 Yaşında!" başlıklı reklam filminde yer alan, *"…Önce halk sonra bankayız biz. Hayatımızın başrolünde halkımız var…"* ifadesidir. Bu ifade ile banka her durumda öncelikle halkı düşündüğünün ve ona göre hareket ettiğinin altını çizerek empatik bir dil kullanmaktadır.

3.4.2. Hizmet Baskın Mantık Kapsamında Reklamlarda "Değerin Ortak Yaratımı" Boyutu

Hizmet baskın mantık, müşteriyi yalnızca üretilen finansal çözümleri tüketen pasif bir alıcı olarak konumlandırmamaktadır. Aksine, müşteriyi kendi operasyonel ve zihinsel kaynaklarını bankanın teknolojik altyapısıyla birleştirerek değeri dinamik olarak birlikte üreten (co-creator) aktif bir ortak olarak kabul etmektedir. İncelenen reklam filmlerine ait metinlerde bankaların hizmet baskın mantık doğrultusunda değerin ortak yaratımında müşterilerini sürecin içerisine çeken ve yaşanılan deneyimi zenginleştiren bir dil kullandığı görülmektedir.

Örneğin Türkiye İş Bankası A.Ş.'nin "Tüm Ödeme Çözümleri İşPOS'ta!" reklam metninde geçen *"...tahsilat, TR kare kodla ödeme ve daha birçok özellik tek bir uygulamada birleşiyor. İşler kolaylaşıyor. Siz de hemen iş postu indirin. Tüm post çözümlerini cebinizden yönetin"* yönlendirmesi, teknolojik imkânların bir faydaya ve değere dönüşebilmesi için kullanıcının sisteme aktif katılımını, seçme, uygulama ve yönetme özgürlüğünü şart koştuğundan hizmet baskın mantığı doğrudan yansıtan bir örnek oluşturmaktadır. Benzer şekilde yine Türkiye İş Bankası'nın *"..Siz hayallerinizi gerçekleştirirken işinizi büyütme yolunda İş Bankası Genç Kobiyiz paketi yanınızda. Çek ve Pos ayrıcalıklarından avantajlı kredi ve size özel kampanyalara Genç Kobiyiz paketinden aldığınız güçle işinizi büyütün…"* ifadeleri, ortaya çıkacak olan değerin oluşturulmasında ortak hareket etmenin oluşturacağı sinerjiye vurgu yapmakta ve bankanın vaat ettiği değerin oluşumunda müşteri ile bir ortak olarak hareket edeceğine dair yaptığı vurguyu göstermektedir.

Türkiye Halk Bankası A.Ş.'nin genç segmenti hedefleyen "Paraf GençİZ" reklam kampanyasındaki *"Dijital platform indirimiyle asist yapar. Oyun alışverişlerine özel indirimle kontratağa geçer. Online alışveriş indirimiyle golü atar..."* söylemleri, gençlerin gündelik yaşam dinamikleri ile bankacılık hizmetlerinin nasıl eklemlendiğini ve değerin ancak kullanıcının aktif tüketim/yaşam pratikleriyle hayat bulduğunu göstermektedir. Benzer şekilde aynı bankanın "Türkiye'nin İlk Karbon Nötr Kredi Kartı Paraf Doğal!" reklam filmindeki, *"...harcama yaptıkça Fidan ve barınaklara mama bağışı yapan doğa dostu bir kart…"* ifadesinde sürdürülebilirlikle ilgili yaratılan değerin müşterinin harcama yapması sonucunda gerçekleşiyor olması değerin müşteri ve banka ortaklığında yaratıldığına dair net bir ifadedir. Bir diğer örnek ise, Türkiye Vakıflar Bankası T.A.O.'nun "Fidem Mobil ile Verili Tarım, Verimli Tarım" reklam filminde yer alan *"...İndirin FIDEM mobili siz de verili tarımı verimli tarıma dönüştürün…"* ifadesi müşteri ile bankanın el ele vererek değeri ortak yaratacaklarını yansıtmaktadır.

4.4.3. Dijitalleşme Kapsamında Reklamlarda Teknolojik Boyut

Dijitalleşme ve otomasyon süreçleri bankacılık sektörüne vazgeçilemeyecek bir operasyonel hız ve maliyet verimliliği sağlasa da tüketicide "algoritmik gözetim, yapaylık, yabancılaşma ve insansızlaşma" gibi postmodern endişelere yol açabilmektedir. Benzer şekilde tüketiciler dijital ortamda elde edilen kişisel verilerin ve diğer dijital ayak izlerinin güvenilir bir şekilde depolandığından emin olmak istemekte ve verilerin kötü niyetli kullanımı konusunda endişeye kapılabilmektedir. Bu noktada H2H pazarlama modeli, dijitalleşmenin sağladığı kolaylıklardan yaralanmayı olmazsa olmaz bir gereklilik olarak değerlendirirken teknoloji nedeniyle oluşabilen yapaylığı insani mesaj tonlarıyla (high-tech/high-touch dengesi) dengelemeyi önermektedir.

Türkiye Vakıflar Bankası T.A.O'nun "Fidem Mobil ile Verili Tarım, Verimli Tarım" reklam filmine ait, "*Kilometrelerce yükseklikteki uydular, fark yaratan [müzik] yazılımlar ve arkasındaki büyük ekip ne için mi [müzik] çalışıyor? İşte bunun için Vakıf Bank'ın çiftçilerimize özel tarım uygulaması, Fidem mobil ile anlık iklim bilgisi, uzman görüşü, [müzik] güncel borsa hal fiyatları ve çok daha fazlası artık cebinizde. Üstelik şubeye bile gitmeden tanımlı kredinizi kullanabilir, ek hesap ve tarım kart işlemlerinizi gerçekleştirebilirsiniz. İndirin FIDEM mobil ile siz de verili tarımı verimli tarıma dönüştürün.*" ifadesi bankanın güncel teknolojiye sağladığı uyumu ve bu sayede müşterilerine sunduğu fırsatları ve verimlilik imkânını vurgulamaktadır.

Benzer şekilde T.C. Ziraat Bankası A.Ş.'nin "Dünya Çiftçiler Günü Reklam Filmimiz" başlıklı reklam filminde geçen, *"....Ahmet abi. He yine Ziraat Çiftçi platformunda. Tarlasına özel hava durumu takibinden [müzik] sulama zamanlamasına kadar tüm kolaylıklar bu uygulamada. Yeni traktörünü alırken bile kredi başvurusunu uygulamadan yaptı. Bankart Başakla ihtiyaçlarını karşılıyor Hesap hareketlerine de bakıyor. Uygulamadan güncel piyasa fiyatlarını da takip ediyor. Bütçe planlamasını da buradan yapıyor. Bir Ahmet abi mi? Hepsi orada. Özel haberler, güncel duyurular. Bir çiftçinin ihtiyacı olan her şey Ziraat Çiftçi platformunda. İşte bir kargaları kovalayamıyor bu uygulama…."* ifadeleri, bankanın dijital dünyanın imkânlarını sunduğu bankacılık hizmetlerine entegre ederek sadece

bankacılık işlemlerinde değil müşterilerin işleri ile ilgili ihtiyaç duyabileceği bir yardımcı olarak taşıdığı öneme dikkat çekmektedir.

Türkiye İş Bankası A.Ş'nin küresel marka gücüne odaklanan kurumsal reklam metnindeki *"...Sen hayal kurmaya devam et. Türkiye'nin bankası hep yanında. Bugün Avrupa'nın ilk 10 bankası arasında. BRAND FINANCE Avrupa'nın marka gücü en yüksek 8. Bankası"* ifadesi ve yine aynı bankanın "Türkiye İş Bankası Kıvançla Sunar" reklam serisinde yer alan *"...Dünyanın en iyi mobil bankacılık uygulaması yanında mı?..."* ifadeleri, sunulan dijital altyapının arkasındaki kurumsal gücü ve küresel şeffaflığı tescilleyerek tüketicide oluşabilecek finansal ve siber güvensizlik algısını kırmayı amaçlamaktadır.

Yine benzer şekilde Türkiye Halk Bankası A.Ş.'nin "Halkbank 87 Yaşında! Birlikte Daha Nice Yıllara!" reklam filminde yer alan *"...Bu filmde ülkenin dört bir yanında bulunan yüzlerce şubemiz yerine... köklü geçmişimiz yerine o geçmişten gelen güvenle yeni bir gelecek kuran kalpleri tüm gücümüzle... Çünkü biz tam 87 yıldır önce Halk sonra bankayız."* ifadeleri bankanın kurumsal geçmişine ve büyüklüğüne vurgu yaparak tüketicilerde güven oluşturmaya çalışmaktadır. Böylece markaya ve kurumsal itibara güvenen tüketici ilgili markanın dijital uygulamalarına da daha endişesiz bir yaklaşım sergileyebilecektir.

SONUÇ

Bu çalışma, bankacılık gibi üst düzeyde dijitalleşen (high-tech) ancak doğası gereği güven, sadakat ve yakınlığa duyulan ihtiyacın son derece yüksek olduğu (high-touch) bir sektörde, Kotler vd. (2021a) tarafından literatüre kazandırılan H2H pazarlama modelinin kurumsal reklam stratejilerindeki yansımalarını nitel içerik analiziyle ortaya koymuştur. Bu kapsamda Türkiye'nin ilk 5 bankasının 15.07.2025 – 15.07.2026 tarihleri arasındaki 172 reklam filmi, Türk bankacılık sektörünün geleneksel ve işlemsel pazarlama mantığından (B2B/B2C), insanı merkeze alan H2H pazarlama paradigmasına doğru bir dönüşüm içerisinde olduğunu göstermektedir. Ancak bu dönüşüm H2H pazarlama modelini oluşturan her boyut için aynı ölçüde söz konusu değildir.

Araştırmadan elde edilen bulgular, bankaların reklam söylemlerinde en çok "Tasarım Odaklı Düşünme" (159 frekans) boyutuna başvurduğunu kanıtlamaktadır. Bankalar, müşteriyi yalnızca bir hesap numarası, finansal veri yığını ya da kârlılık segmenti olarak görmek yerine, toplumsal değerleri, ailevi bağları, gündelik yaşam koşturmacalarını ve duygusal ihtiyaçları olan "bütüncül bir insan" olarak konumlandırmaktadır. Bu durum, sektörün tüketiciyle bağ kurarken duygusal zekâya ve empatiye dayalı iletişim stratejilerini birincil kaldıraç olarak kullandığını göstermektedir.

İkinci sırada yer alan "Hizmet Baskın Mantık" (77 frekans) boyutu ise, mobil şubeler, puan sistemleri, yeşil kart harcamaları ve dijital platform entegrasyonları aracılığıyla müşterinin pasif bir alıcı olmaktan çıkarılarak finansal ve toplumsal faydayı bankayla birlikte üreten aktif bir ortak haline getirildiğini göstermektedir.

Bununla birlikte, çalışmanın ortaya koyduğu en çarpıcı ve stratejik bulgu, "Dijitalleşme" boyutunun reklam içeriklerinde oldukça zayıf (yalnızca 42 frekans) kalmış olmasıdır. Bankacılık işlemlerinin ezici bir çoğunluğunun mobil ve dijital kanallara kaydığı günümüz finans dünyasında, reklamların bu boyutta yetersiz kalması önemli bir stratejik çelişkiye işaret etmektedir. Bankaların reklam mesajlarında dijitalleşme ile sağladıkları kolaylıkları ve ulaştıkları seviyeyi daha görünür kılmalarının özellikle imaj konusunda katkı sağlayabileceği değerlendirilmektedir. Diğer taraftan dijitalleşmenin değinildiği sınırlı sayıdaki reklam mesajında bankalar teknolojiyi hıza dayalı bir işlem kolaylığı olarak sunmakta, ancak dijitalleşmenin tüketicide yarattığı "insansızlaşma, yapaylık, algoritmik gözetim ve veri güvenliği" gibi temel kaygılara reklam söylemlerinde yeterince yanıt verememektedir. Dijitalleşme boyutu, yalnızca uygulamaların indirilmesini teşvik eden teknik bir yönlendirme olarak kalmakta olup insani dokunuşla (high-touch) harmanlanmış özgün bir güven vaadine dönüştürülememektedir.

Sonuç olarak, yapay zekânın, algoritmaların ve otomasyonun baskın olacağı geleceğin finansal pazar ortamında sürdürülebilir bir rekabet avantajı elde etmek isteyen bankaların; İnsan-Makine uyumunu (symbiosis) reklam söylemlerine aktarmaları, dijitalleşmenin getirdiği mekanik soğukluğu, şeffaflık, köklü geçmiş ve "daima yanında olma" vaadi gibi özgün güven unsurlarıyla dengelemeleri ve tüm kurumsal stratejilerini H2H pazarlama modeliyle olgunlaştırmaları kaçınılmaz bir stratejik zorunluluk olarak değerlendirilmektedir.

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DİJİTAL LİNÇ KÜLTÜRÜ VE MARKA KRİZLERİ BAĞLAMINDA SCHADENFREUDE ÜRETİMİ

SCHADENFREUDE GENERATION IN THE CONTEXT OF DIGITAL LYNCH CULTURE AND BRAND CRISES

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ÖZET

Bu çalışma, sosyal medya krizleri ve iptal kültürü bağlamında, tüketicilerin bir markanın yaşadığı talihsizlikten ya da krizden duyduğu hazzı ifade eden schadenfreude duygusunun nasıl üretildiğini incelemektedir. Bu karmaşık duygunun markaya yönelik ekonomik davranışları hangi özgül mekanizmalar üzerinden aşındırdığını açıklayan bütünleşik bir kavramsal çerçeve geliştirmeyi amaçlamaktadır. Kavramsal model; dijital marka krizi, dijital sosyoloji, ahlaki duygular, tüketici intikamı ve negatif elektronik ağızdan ağıza iletişim (eWOM) yazınlarını bir araya getirmektedir. Önerilen çerçeveye göre; algılanan ahlaki ihlalin şiddeti, kurumsal kasıt, yüksek marka statüsü ve tüketici ile marka arasındaki değer uyumsuzluğu gibi faktörler, hak edilmişlik yargısı, kötü niyetli haset ve tüketici–marka özdeşleşmemesi aracılığıyla tüketicinin hissettiği schadenfreude seviyesini doğrudan güçlendirmektedir. Schadenfreude yalnızca pasif ve içsel bir haz olarak kalmayıp, tüketicinin intikam güdüsünü normatif olarak meşrulaştırabilir. Bu durum; dijital ortamlarda gloat etme (böbürlenerek sevinme), yoğun negatif ağızdan ağıza iletişim, boykotlara aktif katılım ve marka kaçınması yollarıyla kolektif bir cezalandırma eylemine dönüşebilmektedir. Sergilenen bu cezalandırıcı davranışlar, markaya duyulan güveni, tüketiciyle olan ilişki kalitesini ve fiyat primi ödemeyi haklılaştıran sembolik değeri derinden sarsarak, nihayetinde tüketicilerin yeniden satın alma niyetini ve ödeme istekliliğini belirgin biçimde düşürmektedir. Bununla birlikte, modeldeki bu pazar etkilerinin doğrusal veya evrensel olmadığı; platform pekiştirmesi, rakip marka özdeşleşmesi, yaşanan krizin türü, kriz öncesi marka değeri ve samimi bir özür ile düzeltici eylem bileşiminin bu ilişkileri düzenleyen kritik sınır koşulları olduğu ileri sürülmektedir. Sonuç olarak çalışma, ampirik olarak test edilebilir beş temel önerme sunmakta ve schadenfreude kavramını yalnızca krizin duygusal bir sonucu değil, marka değerinin ekonomik olarak aşınmasına aracılık eden temel bir geçiş mekanizması şeklinde konumlandırmaktadır.
Anahtar kelimeler: iptal kültürü, dijital linç, marka krizi, schadenfreude, tüketici intikamı, negatif eWOM, yeniden satın alma niyeti, ödeme istekliliği

ABSTRACT

This comprehensive conceptual paper develops an integrated framework explaining how consumer schadenfreude—the feeling of malicious joy derived from a brand's misfortune—emerges during social media firestorms and cancel culture episodes, and how this specific emotion eventually erodes downstream economic responses. The proposed framework extensively connects existing research on digital brand crises, moral emotions, digital sociology, consumer revenge, and negative electronic word of mouth (eWOM). According to the model, factors such as perceived moral transgression, institutional intentionality, high target brand status, and value incongruence between the consumer and the brand significantly intensify schadenfreude. This intensification occurs specifically through mediating mechanisms of deservingness judgments, malicious envy, and strong consumer–brand disidentification. Schadenfreude does not simply remain a passive or internal psychological state; rather, it actively legitimizes revenge motives among consumers. Consequently, it becomes visible through public gloating, widespread negative eWOM, active participation in organized boycotts, and general brand avoidance. These collective retaliatory responses fundamentally weaken brand trust, degrade customer relationship quality, and destroy the symbolic basis required to justify price premiums. Ultimately, these factors severely reduce the consumer's repurchase intention and their willingness to pay. However, the proposed relationships are conditional rather than purely universal. The study identifies platform-based algorithmic reinforcement, rival-brand identification, crisis type, pre-crisis brand equity, and a sincere apology combined with verifiable corrective action as critical boundary conditions.

Finally, the paper provides five empirically testable propositions, deliberately positioning schadenfreude not merely as an emotional aftermath, but as a critical transition mechanism driving collective market punishment and long-term economic erosion.
Keywords: cancel culture, social media firestorm, brand crisis, schadenfreude, consumer revenge, negative eWOM, repurchase intention, willingness to pay

1. Giriş

Dijital platformlar, kurumsal hataların görünürlüğünü artırmakla kalmamış; bu hataların yorumlanma, ahlaki olarak sınıflandırılma ve ekonomik yaptırıma dönüştürülme biçimini de değiştirmiştir. Geleneksel marka krizlerinde bilgi akışı büyük ölçüde kurumsal iletişim kanalları ve haber medyası tarafından düzenlenirken, sosyal medya ekosisteminde tüketiciler aynı anda tanık, yorumcu, yayıcı ve yaptırım uygulayıcı hâline gelebilmektedir. Bu çoklu rol, marka krizini tekil bir olaydan çıkarıp ağlar içinde yinelenen, yeniden çerçevelenen ve performatif olarak sergilenen bir toplumsal sürece dönüştürür. Hansen vd.'nin (2018) bulguları, sosyal medya ateş fırtınalarının markaların kısa dönemli algılarını çoğu vakada bozduğunu ve etkilerin kayda değer bir bölümde uzun döneme taşındığını göstermektedir. Dolayısıyla dijital kriz, yalnızca itibar yönetiminin geçici bir kesintisi değil, marka çağrışımlarının bellekte yeniden örgütlenmesine yol açabilen bir değer aşınması sürecidir.

İptal kültürü, bu sürecin en görünür fakat aynı zamanda en tartışmalı biçimlerinden biridir. Kavram, ırkçılık, din, çevresel sorumluluk veya jeopolitik tutumlar gibi kimlik ve değer yüklü meselelerde bir aktöre desteğin geri çekilmesini, görünürlüğünün azaltılmasını ve kamusal olarak cezalandırılmasını anlatır (Costa & Azevedo, 2024). Ancak her çevrim içi eleştiriyi "dijital linç" olarak nitelemek analitik olarak sorunludur. Hesap verebilirlik talebi, kanıta dayalı tüketici şikâyeti ve örgütlü boykot; tehdit, hedef gösterme, bağlam çökmesi ve orantısız kitlesel saldırıyla aynı kategoriye yerleştirilemez. Bu çalışma dijital linci, eleştirinin ölçek, süre, kişiselleştirme ve yaptırım yoğunluğu bakımından orantısızlaştığı; ağ etkileriyle bireysel değerlendirmeyi aşarak kolektif cezalandırmaya dönüştüğü sınır durum olarak ele almaktadır.

Sosyal medya ateş fırtınalarının gücü, olumsuz bilginin hızından çok, ahlaki değerlendirmeyi görünür sosyal normlara dönüştürmesinden kaynaklanır. Ahlaki öfke ifadeleri olumlu sosyal geri bildirim aldıkça gelecekteki öfke ifadesi güçlenmekte ve kullanıcılar içinde bulundukları ağın ifade normlarına uyum göstermektedir (Brady vd., 2021). Hashtag'ler, yeniden paylaşım, kısa video ve alıntılı gönderi gibi platform olanakları, merkezi bir liderlik olmaksızın ortak bir ihlal anlatısı kurulmasına izin verir. Böylece bireysel memnuniyetsizlik; kimlik sinyalleme, dayanışma gösterisi ve norm uygulama davranışıyla birleşir. Uyar vd. (2026), dijital boykotların yalnızca satın almama değil, kurumsal kanalların yetersiz görüldüğü durumlarda siyasal ve ahlaki iddia taşıyan iletişimsel pratikler olduğunu vurgulamaktadır.

Bu ağlaşmış tepkinin duygusal çekirdeğinde öfke, tiksinti, küçümseme, ihanet ve utanç gibi olumsuz duygular yer alır. Delgado-Ballester vd. (2021), çevrim içi ateş fırtınasının başlatılmasında öfke ve marka hoşnutsuzluğunun belirleyici olduğunu; üzüntünün tek başına misilleme için yeterli motivasyon üretmediğini göstermektedir. Değer ve kimlik uyumsuzluğu da marka nefretini besleyerek satın almama, negatif ağızdan ağıza iletişim ve misillemeye dönüşebilir (Kamboj & Sharma, 2023; Zahid vd., 2026). Burada duygu, özel bir içsel durum olmaktan çıkar; paylaşılabilir içerik biçimleriyle kamusal bir konum beyanına ve pazar yaptırımına çevrilir.

Bununla birlikte dijital tepkinin yalnızca olumsuz duygularla açıklanması eksiktir. Bir markanın düşüşü, kimi tüketiciler için adaletin yerini bulduğu, yüksek statülü bir aktörün hak ettiği sonuca ulaştığı veya daha önce benimsenmiş bir karşıt kimliğin doğrulandığı hissini üretebilir. Bu haz, schadenfreude kavramıyla açıklanır. Schadenfreude'nin marka krizlerindeki özgül rolü, öfke ya da nefretin niceliksel bir uzantısı olmamasıdır: kişi krize doğrudan maruz kalmasa da hedefin talihsizliğini olumlu bir sonuç olarak deneyimleyebilir. Böylece kriz, mağduriyet temelli tepkilerin yanında gözlemci hazzını ve rakip toplulukların sevinçli katılımını da harekete geçirir.

Çalışmanın temel sorusu şudur: Sosyal medya krizlerinde algılanan kurumsal ihlal hangi değerlendirme süreçleriyle schadenfreude üretmekte ve bu haz, tüketici intikamı ile negatif elektronik ağızdan ağıza iletişim üzerinden yeniden satın alma niyeti ve ödeme istekliliğini nasıl aşındırmaktadır? Bu soruya yanıt vermek için marka krizi, tüketici–marka özdeşleşmesi, hak edilmişlik, haset, ahlaki duygular, intikam ve anti-tüketim yazınları bütünleştirilmektedir. Kuramsal katkı, schadenfreude'yi kriz girdileri ile ekonomik çıktılar arasındaki bir "duygusal geçiş mekanizması" olarak konumlandırmaktır.

Bu yaklaşım, dijital krizin etkisini yalnızca olumsuz marka tutumu üzerinden değil, tüketicinin markanın kaybını ödüllendirici bulması ve bu ödülü sosyal dolaşıma sokması üzerinden açıklar.
Çalışma kavramsal niteliktedir ve nedensel etkileri ampirik olarak kanıtladığını iddia etmez. Özellikle ödeme istekliliği konusunda mevcut yazın, doğrudan fiyat primi ölçümlerinden çok satın alma niyeti, boykot, finansal fedakârlık ve marka kaçınması göstergelerine dayanmaktadır. Bu nedenle "kalıcılık" varsayımı koşulsuz bir sonuç olarak değil; kriz belleği, tekrar maruz kalma, sosyal pekiştirme ve yetersiz telafi altında sınanması gereken zamansal bir önerme olarak ele alınmaktadır. Bu eleştirel sınır, kavramsal modelin yanlış bir determinizme dönüşmesini engeller.

1.1. Ateş Fırtınasından Kolektif Yaptırıma

Bir sosyal medya krizinin etkisi, tetikleyicinin canlılığı, ürünle doğrudan ilişkisi, mesaj hacmi ve dolaşım süresi arttıkça güçlenmektedir (Hansen vd., 2018). Bu özellikler yalnızca erişimi artırmaz; aynı ihlal çerçevesinin tekrarlanmasıyla bilişsel erişilebilirliği ve marka–kusur çağrışımını pekiştirir. Tüketici tarafından üretilen iletişimin marka değeri ve marka tutumu üzerindeki etkisi, kurumsal olarak üretilen iletişimin etkisinden daha geniş olabilmektedir (Schivinski & Dabrowski, 2016). Bu nedenle kriz, markanın söylemsel egemenliğinin zayıfladığı ve anlatı üretim kapasitesinin dağıtık aktörlere geçtiği bir dönemdir.
İptal sürecinin pazar sonucu, görünür onay ve yaptırım sinyallerinin karşılıklı beslenmesiyle oluşur. Paylaşım sayıları, eğilim listeleri ve yorum kümeleri ihlalin toplumsal önemine ilişkin sezgisel kanıt sunar; tüketici, tepkinin haklılığı kadar yaygınlığına da bakar. Bu sinyalleme mantığı, belirsiz bir olayın ahlaki kesinlik kazanmasını hızlandırabilir. Bunun riski, bağlamı sınırlı bilgilerin çoğunluk işaretiyle doğruluk kazanmasıdır. Öte yandan aynı mekanizma, kurumsal olarak bastırılmış mağdur anlatılarının görünür olmasını da sağlayabilir. Dolayısıyla dijital kolektif yaptırım, ne özünde irrasyonel bir kalabalık davranışı ne de kendiliğinden meşru bir hesap verebilirlik biçimidir; değerlendirilmesi kanıt kalitesi, orantılılık ve hedeflenen davranışın niteliğine bağlıdır.
Markaların kriz karşısındaki yanıtları bu sürecin yönünü değiştirebilir. Özür, negatif içeriğin yeniden iletilmesini azaltmada çoğu durumda etkili olmakla birlikte, somut şikâyetlerde düzeltici eylemle benzer bir performans göstermektedir (Langaro vd., 2024). İptal kültürü bağlamında özür, bağışlama ve satın alma niyetini destekleyebilir (Costa & Azevedo, 2024). Bununla birlikte özrün sembolik kalması, gecikmesi veya markanın önceki tutumuyla çelişmesi ikiyüzlülük atıflarını güçlendirebilir. Hatta ahlaki temelli bazı ateş fırtınalarında markanın tutarlı biçimde karşılık vermesi, destekçi toplulukları harekete geçirerek marka değerini koruyabilir (Scholz & Smith, 2019). Bu çeşitlilik, tek bir "her zaman özür dile" reçetesinin kuramsal olarak yetersiz olduğunu göstermektedir.

2. Tüketici Davranışında Schadenfreude: Marka Hatalarından Duyulan Haz

Schadenfreude, bir başkasının talihsizliğinin gözlemcide olumlu duygulanım üretmesidir. Tüketici araştırmalarında bu duygu, özellikle statü ürünlerinin başarısızlığı, rakip markanın gerilemesi ve ahlaki ihlal içeren kurumsal krizler bağlamında incelenmiştir (Sundie vd., 2009; Ruppel & Einwiller, 2021). Kavramın analitik önemi, hedefe verilen zararın kişinin maddi çıkarını doğrudan artırması gerekmemesidir. Haz, göreli konumun düzelmesi, adalet beklentisinin karşılanması veya kimliğin doğrulanması gibi psikolojik kazançlardan doğabilir. Bu nedenle schadenfreude, salt "kötülük" etiketiyle açıklanamayacak; sosyal karşılaştırma, hak edilmişlik ve grup ilişkileri içinde şekillenen karmaşık bir ahlaki duygudur.
Schadenfreude öfke, nefret ve tiksintiden ayrılmalıdır. Öfke, bir ihlali düzeltmeye ve faille yüzleşmeye yönelen yüksek uyarılmalı olumsuz bir duygudur; nefret hedefin kalıcı biçimde kötü olduğuna ilişkin bütünsel bir değerlendirme içerebilir; tiksinti ise temastan kaçınmayı tetikler. Schadenfreude ise hedefin kaybına ilişkin olumlu değerlemeyi ifade eder. Bu duygular eşzamanlı ortaya çıkabilir, fakat işlevleri özdeş değildir. Marka krizi yaşayan bir tüketici öfkeli olmadan da rakip markanın düşüşünden memnuniyet duyabilir; tersine, doğrudan mağdur olan kişi yoğun öfke yaşarken hazzı deneyimlemeyebilir. Kavramsal ve ampirik ölçümlerde bu ayrımın korunması, ortak yöntem varyansını ve yapısal örtüşmeyi azaltmak için kritiktir.
Tüketici schadenfreude'sinin ilk temel öncülü sosyal karşılaştırma ve hasettir. Yüksek statülü bir ürün ya da markanın sağladığı görünür sosyal avantaj, gözlemcide göreli yoksunluk yaratabilir. Ürün başarısız olduğunda, statü farkının sembolik olarak daralması haz üretir (Sundie vd., 2009). Pancer vd. (2017), ürün statüsü ile hak edilmişlik yargısının schadenfreude'yi birlikte şekillendirdiğini göstermektedir. Ekonomik hareketliliği sınırlı algılayan tüketiciler, başarılı markaların üstünlüğünü

daha az hak edilmiş değerlendirebilir; markanın toplumsal katkı sinyalleri zayıf olduğunda bu kötü niyetli haset artabilir (Bak & Yi, 2024). Bu bulgular, fiyat ve prestij iletişiminin yalnızca arzu değil, kırılgan bir karşılaştırmalı üstünlük de ürettiğine işaret eder.

İkinci öncül hak edilmişlik değerlendirmesidir. Bir kriz kasıtlı, önlenebilir veya ahlaki olarak ağır görüldüğünde, markanın kaybı rastlantısal bir talihsizlikten çok uygun bir ceza olarak anlamlandırılır. Hak edilmişlik bu noktada ahlaki bir lisans işlevi görür: başkasının acısından haz duyma normatif olarak rahatsız edici olsa da "marka bunu hak etti" yargısı hazzı meşrulaştırır. Bu mekanizma, ürün performans hataları ile değer krizleri arasında ayrım yapılmasını gerektirir. Yanlışlıkla oluşan ve hızla telafi edilen bir teknik arıza, kurumsal kasıt veya sistematik sömürü içeren bir skandalla aynı düzeyde schadenfreude üretmemelidir.

Üçüncü öncül tüketici–marka özdeşleşmemesi, başka bir ifadeyle tüketicinin markayı benliğine karşıt bir simge olarak konumlandırmasıdır (Anaza vd., 2021). Ruppel ve Einwiller (2021), özdeşleşmeyen tüketicilerin marka krizini önceki reddedişlerini doğrulayan bir fırsat olarak gördüğünü; öfke, küçümseme ve tiksintiyle uyumlu schadenfreude'nin negatif ağızdan ağıza iletişim, kaçınma ve cezalandırma davranışlarına aracılık ettiğini ortaya koymaktadır. Özdeşleşmeme, basit düşük bağlılıktan farklıdır: tüketici markayı ilgisiz bulmaz, aktif olarak "ben olmayanı" temsil eden bir karşı kimlik nesnesi olarak görür. Bu nedenle kriz, benlik doğrulayıcı bir sembolik kazanç sağlar.

Dördüncü öncül grup rekabeti ve rakip marka özdeşleşmesidir. Özellikle spor, teknoloji, otomotiv ve lüks tüketim gibi güçlü marka topluluklarının bulunduğu pazarlarda, bir rakibin başarısızlığı iç grubun göreli statüsünü artırabilir. Grup düzeyinde aşağı konumlanma acısı, başarılı dış grubun kaybından duyulan hazzı salt kişisel hasetten daha güçlü biçimde açıklayabilir (Leach & Spears, 2008). Böylece tüketici, krizi yalnızca marka hakkındaki bilgi olarak değil, "biz" ve "onlar" arasındaki rekabetin skoru olarak işler. Liao vd. (2023), rakip marka özdeşleşmesinin rakip hakkındaki negatif ağızdan ağıza iletişimi schadenfreude aracılığıyla güçlendirdiğini göstermektedir.

Schadenfreude'nin dijital ortamda görünür hâle gelmesi, gloat etme veya böbürlenerek sevinme davranışı üzerinden gerçekleşir. Alaycı yorum, meme, ironi, başarısızlık derlemesi ve yeniden paylaşım, içsel hazzı kamuya açık bir performansa dönüştürür. Hornik vd. (2019), örgütsel gerileme sonrasında gloat etmenin kötü niyetli elektronik ağızdan ağıza iletişimi beslediğini belirtmektedir. Burada içerik ile duygu birbirini güçlendirir: mizah paylaşılabilirliği artırırken paylaşım sayısı olayın "hak edilmiş" olduğu izlenimini pekiştirir. Ancak mizah, eleştirinin ahlaki sorumluluğunu görünmez kılabilir ve saldırganlığı sosyal olarak kabul edilebilir bir forma sokabilir.

Gözlemci dinamikleri, schadenfreude'nin markaya dolaylı zarar verebileceğini göstermektedir. Bir şikâyetçiye karşı marka savunucularının veya trollerin alaycı tepkileri, diğer kullanıcılar tarafından kötü niyetli haz olarak algılanabilir. Bacile vd. (2025), özellikle sadık müşteri personasının şikâyetçiyi küçümseyen yorumlarının gözlemcide şikâyetçiye sempatiyi artırarak satın alma niyetini düşürdüğünü bulmuştur. Bu sonuç, "marka topluluğu savunması"nın her zaman koruyucu olmadığını; kontrolsüz savunuculuğun markanın empati yoksunu görünmesine neden olabileceğini ortaya koyar.

2.1. Öncüller, Değerlendirmeler ve Sınır Koşulları

Tablo 1, kavramsal modelde yer alan temel yapıların analitik ayrımını ve önerilen işlevini özetlemektedir.

Tablo 1. Kavramsal modeldeki temel yapılar

Yapı	Kavramsal tanım	Modeldeki işlev
Algılanan ihlal	Marka davranışının etik, toplumsal veya işlevsel beklentileri aşması	Krizi ahlaki olarak sınıflandıran başlangıç uyarıcısı
Hak edilmişlik	Markanın uğradığı kaybın uygun ve orantılı bir sonuç olduğu yargısı	Schadenfreude'yi normatif olarak meşrulaştıran değerlendirme
Haset	Markanın statüsü veya avantajı karşısında hissedilen karşılaştırmalı eksiklik	Yüksek statülü hedefin düşüşünü ödüllendirici kılar
Özdeşleşmeme	Markanın benliğe ve iç grup kimliğine karşıt bir simge olarak görülmesi	Krizi kimlik doğrulama fırsatına dönüştürür

Schadenfreude	Markanın talihsizliği karşısında hissedilen olumlu duygulanım	Kriz değerlendirmelerini cezalandırıcı davranışa bağlayan duygusal geçiş
İntikam güdüsü	Markaya zarar vererek adaleti veya dengeyi yeniden kurma isteği	Hazzı amaçlı misillemeye dönüştürür
Negatif eWOM	Markaya ilişkin olumsuz içeriğin dijital ağlarda üretilmesi ve iletilmesi	Kolektif görünürlük ve itibar aşınması yaratır

Schadenfreude'nin ortaya çıkışı otomatik değildir. Öncelikle hedefin insanlaştırılma düzeyi önemlidir: soyut bir "şirket"e duyulan haz, işini kaybeden çalışanlar veya zarar gören tüketiciler görünür olduğunda empatiyle sınırlandırılabilir. İkinci olarak nedensellik atfı belirleyicidir. Algoritma kaynaklı hatalarda tüketiciler, insan kaynaklı hatalara kıyasla daha düşük failiyet ve sorumluluk atfedebilir ve daha ılımlı tepki gösterebilir (Srinivasan & Sarial-Abi, 2021). Bununla birlikte "algoritmik otonomi" markayı sorumluluktan bütünüyle kurtarmaz; algoritmanın tasarımı, gözetimi ve düzeltilebilirliği kurumsal kontrol altındaysa sorumluluk yeniden markaya yüklenebilir.

Üçüncü olarak öncül marka itibarı ve kurumsal sosyal sorumluluk, ihlalin tekil sapma mı yoksa kurumsal özün göstergesi mi olduğuna ilişkin çıkarımları etkiler. Güçlü bir kriz öncesi sosyal sorumluluk itibarı, ihanet hissini ve misilleme niyetini zayıflatabilir; ancak bu tampon kriz türüne bağlıdır (Kang vd., 2021; Ahmed vd., 2025). Dördüncü olarak kriz yanıtı, pişmanlık ve onarım sinyali üretir. Samimi özür, sorumluluğu kabul ederken düzeltici eylem gelecekteki zararın azaltılabileceğini gösterir. Sinyalleme kuramı açısından en inandırıcı yanıt, marka için maliyetli ve doğrulanabilir taahhütler içeren yanıttır; ucuz sözler schadenfreude'yi besleyen ikiyüzlülük atıflarını azaltmakta yetersiz kalabilir.

3. Tüketici İntikamı ve Negatif Ağızdan Ağıza İletişim

Schadenfreude, hedefin kaybını ödüllendirici kılan bir duygu olsa da tek başına davranış değildir. Tüketici intikamı, algılanan adaletsizliği gidermek, güç dengesini yeniden kurmak veya hedefe bedel ödetmek amacıyla gerçekleştirilen kasıtlı karşı davranışları ifade eder. Bu ayrım, duygudan eyleme geçişi açıklamak için gereklidir. Schadenfreude tüketiciye markanın cezalandırılmasının iyi bir sonuç olduğu duygusunu verir; intikam güdüsü ise bu sonucun üretilmesine aktif olarak katkı sunma isteğini oluşturur. Negatif elektronik ağızdan ağıza iletişim (negative eWOM/NWOM), düşük maliyetli, yüksek görünürlüklü ve başkalarının kararlarını etkileyebilen bir misilleme aracı olarak bu geçişin başlıca davranışsal çıktısıdır.

İntikam güdüsü, özellikle hizmet başarısızlığı, adaletsiz telafi ve ihanet algısı altında güçlenir. Wen-Hai vd. (2019), dışa dönük ve içe dönük olumsuz duyguların intikam arzusu üzerinden negatif ağızdan ağıza iletişimi etkileyebildiğini göstermektedir. Sevilen bir markanın ihlali de ilişki yatırımını korumak yerine yoğun bir ihanet ve utanç süreci doğurabilir; tatminsizlikten ihanete ve marka utancına uzanan ardışık değerlendirmeler misilleme ve negatif iletişimi artırabilir (Baghi & Gabrielli, 2021; Weitzl & Hutzinger, 2025). Bu bulgu, güçlü bağın her zaman koruyucu olmadığını; beklenti ihlalinin kişisel algılandığı durumlarda "yüksekten düşüş" etkisi yaratabileceğini gösterir.

Schadenfreude'nin NWOM üzerindeki etkisi iki yoldan ilerleyebilir. Doğrudan yolda tüketici, olumsuz haberi paylaşmanın kendisini sürdürmekten ve sosyal onay toplamaktan haz duyar. Dolaylı yolda ise hazzın ürettiği haklılık hissi intikam güdüsünü güçlendirir; tüketici paylaşımı markanın itibarına zarar vermek, diğerlerini satın almaktan caydırmak veya boykotu büyütmek için kullanır. Rakip marka özdeşleşmesi birinci yolu, kişisel ihanet ve adaletsizlik ise ikinci yolu daha fazla besleyebilir. Bu iki yolun ampirik olarak ayrıştırılması, niyet ile davranış arasındaki farklılığı ve paylaşımın eğlence, uyarı ya da cezalandırma amaçlarını ölçmeyi gerektirir.

Negatif eWOM tek güdülü bir davranış değildir. Tüketici başkalarını uyarmak, bilgi asimetrisini azaltmak, destek aramak, duygusunu boşaltmak veya kamusal bir normu savunmak için de olumsuz içerik paylaşabilir (Ribeiro & Kalro, 2023). Bu nedenle her olumsuz paylaşımı intikam olarak kodlamak hem kavramsal geçerliliği bozar hem de meşru tüketici sesini patolojikleştirir. İntikam yönelimli NWOM'u ayırt eden özellik, markaya zarar vermenin davranışın asli veya araçsal amacı olmasıdır. Uyarı yönelimli NWOM'da ise birincil amaç diğer tüketicilerin zarar görmesini engellemektir; markanın kaybı ikincil bir sonuçtur.

Dijital ortam NWOM'un erişimini, kalıcılığını ve yeniden üretilebilirliğini artırır. Olumsuz içerik ekran görüntüsü, arşiv, arama sonucu ve öneri sistemi aracılığıyla ilk kriz bağlamından koparak yeniden dolaşıma girebilir. Hornik vd. (2019), gloat etme içeren kötü niyetli eWOM'un daha hızlı ve geniş yayılabileceğine işaret eder. Algoritmik sıralama sistemleri yüksek etkileşimli öfke ve alay içeriklerini görünür kıldığında, platform tarafsız bir taşıyıcı olmaktan çıkar ve duygusal yoğunluğun seçici çoğaltıcısına dönüşür. Bu çoğaltma, kullanıcıların çoğunluk algısını ve davranışın meşruluğunu etkileyen bir sosyal kanıt üretir.

NWOM aynı zamanda geri beslemeli bir tırmanma mekanizmasıdır. Paylaşım, tüketicinin olumsuz kimlik pozisyonuna kamusal bağlılığını artırabilir; geri adım atmanın psikolojik maliyeti yükselir. Yeni kullanıcı yorumları ihaneti, marka nefretini ve sabote etme isteğini güçlendirebilir. Sameeni vd. (2024), yoğun negatif eWOM'un dolaylı intikam yoluyla kapanış sağlamadığında daha saldırgan davranışlara tırmanabileceğini; kişilik özelliklerinin de bu süreci düzenlediğini göstermektedir. Marka sabotajı, zarar vermenin araç değil baskın amaç hâline geldiği noktada araçsal misillemeden ayrılır (Kähr vd., 2016). Bu ayrım, kriz yöneticilerinin her yüksek hacimli olumsuzluğu aynı yanıt stratejisiyle ele almaması gerektiğini gösterir.

Kriz iletişimi, duygudan misillemeye geçişte kritik bir kesinti noktası sunar. Empatik bir marka yanıtı, haksız veya aşırı NWOM'a tanık olan tüketicilerde markaya yönelik olumlu değerlendirmeyi destekleyebilir (Allard vd., 2020). Buna karşılık alaycı kurumsal ton saldırgan algılanabilir; tüketici nezaketsizliğine verilen iddialı fakat saygılı yanıt daha etkili olabilir (Batista vd., 2022). Marka, haklı eleştiriyi susturmaya çalışmak yerine zarar gören tarafı tanımalı, sorumluluk alanını açıkça belirtmeli ve doğrulanabilir düzeltme sunmalıdır. Bu yaklaşım, schadenfreude'nin meşruiyet dayanağı olan "hak edilmiş ceza" algısını zayıflatabilir.

Yine de kriz müdahalesinin sınırları vardır. Rakip marka topluluğu veya siyasi dış grup için kriz, yalnızca bilgi eksikliği değil, kimlik performansı fırsatıdır. Bu durumda olgusal düzeltme, özdeşleşmeme ve grup rekabetinden kaynaklanan hazzı azaltmayabilir. Dahası markanın tartışmalı tutumundan geri çekilmesi, karşıtları yatıştırırken destekçilerde ihanet yaratabilir (Mukherjee & Althuizen, 2020). Dolayısıyla uygun müdahale, hedef kitlenin duygusal segmentasyonunu; doğrudan mağdurlar, hayal kırıklığı yaşayan sadık müşteriler, rakip taraftarlar, ahlaki aktivistler ve fırsatçı yayıcılar arasındaki ayrımı gerektirir.

3.1. Pasif Hazdan Aktif Cezalandırmaya Geçiş

Pasif hazdan aktif cezalandırmaya geçiş için üç koşul öne çıkmaktadır. Birincisi, markanın kaybının hak edilmiş ve tüketicinin katkısının etkili görülmesidir. Boykot başarısının olası algılanması, katılımı ve satın almama isteğini artırabilir (Shin & Yoon, 2018). İkincisi, davranışın sosyal maliyetinin düşük ve sosyal getirisinin yüksek olmasıdır. Tek tıklamayla paylaşım, tüketicinin kimlik ve ahlaki tutum sinyali vermesini kolaylaştırır. Üçüncüsü, ağın normatif desteğidir. Yüksek görünürlüklü onaylar misilleme davranışını bireysel öfkeden kolektif göreve dönüştürür.

Bu koşullar aynı zamanda dijital linç riskini açıklar. Kanıtın belirsiz olduğu bir olayda etki hissi, düşük davranış maliyeti ve yoğun normatif destek bir araya geldiğinde, yaptırım olayın ağırlığını aşabilir. Böyle bir tırmanmada schadenfreude, eleştirel değerlendirmeyi azaltan ödüllendirici bir geri bildirim işlevi görür. Bu nedenle platform ve marka yönetişimi yalnızca içeriğin olumlu ya da olumsuz olmasına değil; koordineli taciz, yanlış bilgi, hedef gösterme ve tekrarın orantılılığına odaklanmalıdır.

4. Schadenfreude'nin Yeniden Satın Alma Niyeti ve Ödeme İstekliliğine Etkisi

Yeniden satın alma niyeti, tüketicinin önceki deneyim ve güncel değerlendirmeleri temelinde aynı markayı gelecekte tekrar seçme eğilimidir. Ödeme istekliliği ise belirli bir ürün veya marka için kabul edilebilecek en yüksek parasal fedakârlığı ve dolayısıyla marka fiyat priminin talep tarafındaki temelini ifade eder. Marka krizi bu iki sonucu farklı fakat bağlantılı yollarla etkiler. Güven ve ilişki kalitesinin bozulması yeniden satın alma olasılığını düşürürken, sembolik değerin ve ahlaki meşruiyetin aşınması fiyat primini haklılaştıran faydayı azaltır. Schadenfreude, bu aşınmayı yalnızca olumsuz tutumla değil, markanın kaybını olumlu bir sonuç hâline getirerek derinleştirir.

Kurumsal skandalların sadakat üzerindeki etkisi, olay bilgisinin doğrudan etkisinden çok ihanet, utanç, öfke ve marka nefreti gibi duygusal mekanizmalarla ortaya çıkar (Khatoon & Rehman, 2021; Jabeen vd., 2022). Negatif kurumsal itibar marka tutumunu ve satın alma niyetini zayıflatabilir (Jung & Seock, 2016); hizmet bağlamında marka nefreti yeniden satın almama niyetini artırır (Curina vd., 2020). Schadenfreude bu dizide özgül bir rol oynar: tüketici markanın toparlanmasını arzulamak yerine,

düşüşün sürmesini psikolojik olarak ödüllendirici bulabilir. Bu nedenle sıradan tatminsizlikte etkili olan telafi, schadenfreude durumunda daha yüksek bir ikna eşiğiyle karşılaşır.

Yeniden satın alma üzerindeki birinci yol, tutumsal ve ilişkisel kopuştur. Hak edilmişlik yargısı, ihlali geçici bir hata değil markanın karakteri hakkında tanısal bilgi olarak çerçeveler. Tüketici krizden sonra aynı markayı satın almayı, yalnızca işlevsel bir seçim değil, yanlış davranışa rıza veya kimlik tutarsızlığı olarak görebilir. Boykot böylece özel tüketimden kamusal ahlaki konumlanmaya dönüşür. Özellikle satın alma davranışı sosyal olarak görünürse, markaya dönmenin itibar maliyeti yükselir. Negatif eWOM'a daha önce katılmış tüketiciler için tutarlılık baskısı bu maliyeti pekiştirir.

İkinci yol, fırsat setinin yeniden değerlendirilmesidir. Kriz, rakiplerin ahlaki veya sembolik üstünlüğünü görünür kılabilir; tüketici işlevsel maliyeti olsa bile alternatif markaya geçerek hedef markayı cezalandırabilir. Brand hate yazını, tüketicilerin markaya zarar vermek için kişisel maliyet üstlenebildiğini göstermektedir (Sameeni vd., 2024). Bu finansal fedakârlık mantığı, ödeme istekliliğinin yalnızca ürün faydasına değil, alışverişin ahlaki anlamına bağlı olduğunu ortaya koyar. Tüketici, hedef markanın daha ucuz seçeneğini reddedebilir veya alternatif için ek bedel ödeyebilir.

Üçüncü yol, fiyat priminin sembolik dayanağının çökmesidir. Yüksek statülü markalar kalite, seçkinlik, aidiyet ve toplumsal beğeni sinyalleri için fiyat primi talep eder. Kriz markayı utanç, ikiyüzlülük veya sömürüyle ilişkilendirdiğinde, aynı görünürlük artık pozitif statü yerine damgalanma riski taşır. Sosyal olarak kabul edilemez marka anmalarının güçlü öz-bağlantıya sahip tüketicilerde dolaylı utanç ve geri çekilme yaratabildiği gösterilmiştir (Villanova & Matherly, 2024). Böyle bir durumda tüketici ürünün işlevsel faydasını korusa bile sembolik fayda kaybı nedeniyle daha düşük ödeme istekliliği gösterebilir.

Dördüncü yol, tekrar maruz kalma ve kriz belleğidir. Negatif içerik arama sonuçlarında ve platform önerilerinde kalıcılaştıkça, satın alma anında kriz çağrışımı yeniden etkinleşir. NWOM'un hacmi ve süresi, marka hatasının zihinsel erişilebilirliğini artırır; bu, kısa süreli tepkiyi daha uzun süreli kaçınmaya dönüştürebilir. Bununla birlikte "kalıcı düşüş" ifadesi dikkatle kullanılmalıdır. Hansen vd. (2018) bazı markalarda uzun dönemli algı etkileri bildirse de tüm krizlerin geri döndürülemez olduğu sonucuna varılamaz. Bağışlama, yeni olumlu deneyimler, inandırıcı telafi ve zaman içinde azalan erişilebilirlik davranışsal iyileşme sağlayabilir.

Beşinci yol, sosyal bulaşma ve gözlemci etkisidir. Bir kullanıcı krizden doğrudan etkilenmese bile, şikâyetçiye yönelik kaba savunma veya alay gözlemcide sempati ve düşük satın alma niyeti yaratabilir (Bacile vd., 2025). Böylece markanın ekonomik kaybı yalnızca kriz mağdurlarından değil, etkileşimi izleyen sessiz çoğunluktan da gelebilir. Bu mekanizma, sosyal medya ölçümlerinde yalnızca gönderi üretenleri analiz etmenin eksikliğini gösterir; görüntüleyen fakat yorum yapmayan kullanıcıların tutum ve ödeme istekliliği de modele dâhil edilmelidir.

Marka değeri ve bağlanma, bu olumsuz yolları tamponlayabilir. Güçlü marka değeri, ürün geri çağırma krizlerinde olumsuz çevrim içi iletişimin firma değeri üzerindeki etkisini sınırlayabilir (Hsu & Lawrence, 2016). Çevrim içi marka topluluğu katılımı, bağışlama üzerinden yeniden satın alma niyetini destekleyebilir (Yuan vd., 2020). Buna karşılık yüksek bağlılık, bazı çevrim içi gaflarda daha büyük güven ve beğeni kaybı yaratabilir; çünkü bağlı tüketici olayı daha saldırgan ve daha az mizahi değerlendirebilir (Hayran & Ceylan, 2023). Bu karşıt bulgular, bağlılığın doğrusal bir koruyucu değil, kriz türüne ve ihlalin benlik bağına temasına göre tampon veya büyüteç olabilen bir düzenleyici olduğunu düşündürür.

Ödeme istekliliği bakımından doğrudan ampirik kanıtın sınırlı oluşu modelin önemli bir araştırma açığıdır. Moral outrage ve boykot yazını satın alma isteksizliği, marka değerlendirmesi ve kişisel maliyet üstlenme eğilimini güçlü biçimde desteklese de, deneysel açık artırma, teşvik uyumlu fiyat seçimi veya gerçek satış verisi kullanan çalışmalar daha azdır. Ayrıca indirim her zaman iyileştirici olmayabilir: damgalanmış kimlikle sembolik olarak bağlantılı ürünlerde fiyat indirimi saygısızlık olarak algılanarak satın alma niyetini düşürebilir (Du vd., 2025). Bu nedenle kriz sonrası fiyat promosyonu, ahlaki onarımı ikame eden mekanik bir araç olarak görülmemelidir.

Asimetrik ve tersine dönüş etkileri de hesaba katılmalıdır. Tartışmalı bir marka tutumuna katılmayan tüketicilerde tutum ve tercih bozulurken, destekçilerde olumsuz etki sınırlı kalabilir; dış grubun markaya öfkesi, markanın değerlerini paylaşanlarda öz–marka bağını ve satın alma niyetini güçlendirebilir (Mukherjee & Althuizen, 2020; Kermani vd., 2024). Kimlikle kaynaşmış tüketiciler marka performansını ahlaki yargıdan ayırarak desteği sürdürebilir (Kim & Krishna, 2022). Sonuç olarak ortalama etki, birbirine zıt segment etkilerini gizleyebilir; ödeme istekliliği analizlerinde ideolojik uyum ve grup kimliği mutlaka modellenmelidir.

4.1. Ekonomik Aşınmanın Koşulluluğu

Schadenfreude'nin pazar sonuçlarını belirlemesinde üç zaman ufku ayrıştırılmalıdır. İlk aşamada kriz görünürlüğü ve duygusal uyarılma satın alma niyetini hızla düşürür. Orta vadede tüketicinin kamusal olarak aldığı pozisyon, alternatif markaya geçişi ve negatif eWOM yatırımı geri dönüş maliyeti yaratır. Uzun vadede ise etkinin sürmesi, kriz çağrışımının bellekte korunmasına, markanın aynı davranışı tekrar edip etmemesine ve onarım sinyallerinin güvenilirliğine bağlıdır. Böyle bir süreç yaklaşımı, tek bir kriz sonrası anketle "kalıcı etki" çıkarımı yapılmasının önüne geçer.

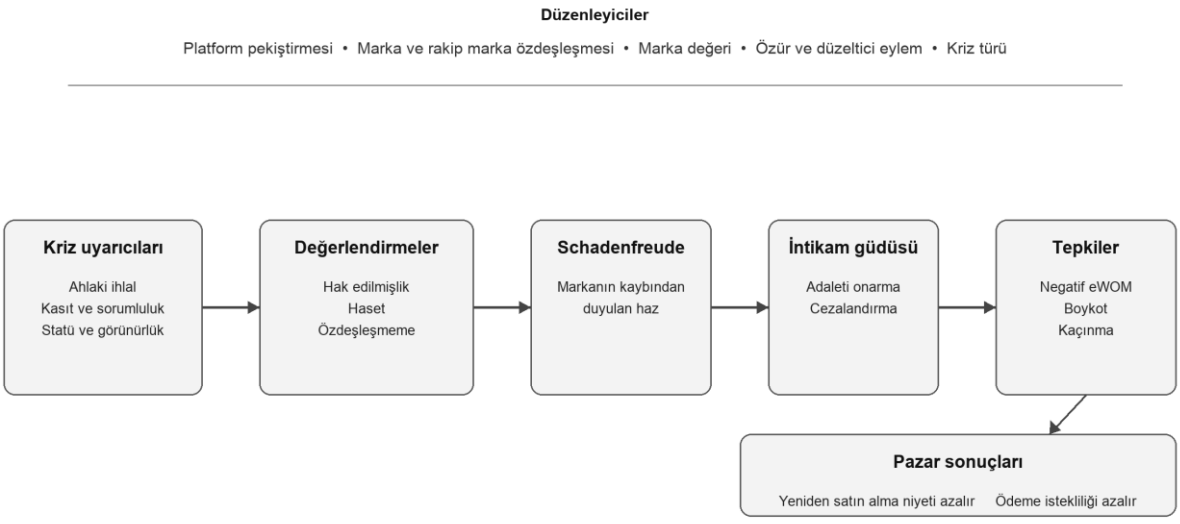
Ekonomik etkinin ölçümünde niyet–davranış açığı ayrıca önemlidir. Tüketiciler sosyal baskı altında boykot niyeti bildirebilir fakat fiyat, erişilebilirlik veya alışkanlık nedeniyle satın almaya devam edebilir. Tersi de mümkündür: kamuya açık tepki vermeyen gözlemciler sessizce markadan uzaklaşabilir. Bu nedenle gelecek araştırmalar beyan edilmiş yeniden satın alma niyetini gerçek tekrar satın alma, sepet verisi, fiyat primi seçimi ve zaman içindeki marka değiştirme davranışıyla eşleştirmelidir.

5. Araştırma Önermeleri ve Kavramsal Çerçeve

5.1. Modelin Bütünleştirici Mantığı

Önerilen model, dijital marka krizini beş aşamalı bir süreç olarak ele almaktadır. Birinci aşamada tüketici, krizin ahlaki ağırlığını, markanın kasıt ve kontrol düzeyini, hedefin statüsünü ve kendi değerleriyle uyumunu değerlendirir. İkinci aşamada bu uyarıcılar hak edilmişlik, haset ve özdeşleşmeme üzerinden duygusal anlam kazanır. Üçüncü aşamada markanın kaybı schadenfreude üretir. Dördüncü aşamada haz, intikam güdüsü ve sosyal pekiştirme yoluyla NWOM, boykot ve kaçınmaya dönüşür. Beşinci aşamada bu davranışlar ilişki kalitesi ile sembolik değeri aşındırarak yeniden satın alma niyeti ve ödeme istekliliğini düşürür.

Model, doğrudan ve dolaylı yolları birlikte içerir. Schadenfreude, tüketicinin markanın toparlanmasına dönük arzusunu azaltarak pazar sonuçlarını doğrudan etkileyebilir; ancak temel beklenti etkinin intikam güdüsü ve negatif eWOM üzerinden kısmen veya tamamen aracılanmasıdır. Platform pekiştirmesi davranışa geçişi; öncül marka değeri ile özür–düzeltici eylem bileşimi ise krizden duyguya ve davranıştan ekonomik sonuca uzanan yolları zayıflatabilir. Rakip marka özdeşleşmesi ve ideolojik uyum ise etkiyi segmentler arasında asimetrik hâle getirir.



Şekil 1. Dijital marka krizlerinde schadenfreude temelli kolektif cezalandırma modeli

5.2. Araştırma Önermeleri

Önerme 1. *Algılanan ahlaki ihlal şiddeti ve kurumsal kasıt arttıkça tüketicinin markaya yönelik schadenfreude düzeyi artar; bu ilişki, markanın uğradığı kaybın hak edilmiş olduğu yargısı tarafından aracılanır.*

Önerme 2. *Yüksek marka statüsü, tüketici–marka özdeşleşmemesi ve rakip marka özdeşleşmesi schadenfreude'yi güçlendirir; yüksek statünün etkisi kötü niyetli haset, özdeşleşmemenin ve rakip özdeşleşmesinin etkisi ise kimlik doğrulama üzerinden ortaya çıkar.*

Önerme 3. *Schadenfreude, negatif elektronik ağızdan ağıza iletişim, boykot ve marka kaçınması eğilimlerini artırır; bu ilişkide tüketici intikam güdüsü kısmi aracı rol oynar.*
Önerme 4. *Schadenfreude'nin negatif elektronik ağızdan ağıza iletişim ve kolektif cezalandırma üzerindeki pozitif etkisi, görünür sosyal onay ve algoritmik etkileşim pekiştirmesi yüksek olduğunda daha güçlüdür.*
Önerme 5. *Schadenfreude, intikam güdüsü ve negatif elektronik ağızdan ağıza iletişim üzerinden yeniden satın alma niyeti ile ödeme istekliliğini dolaylı olarak düşürür; güçlü kriz öncesi marka değeri ile zamanında, sorumluluk kabul eden özür ve doğrulanabilir düzeltici eylem bu olumsuz dolaylı etkiyi zayıflatır.*

Tablo 2. Araştırma önermelerinin ölçülebilir bileşenleri

Önerme	Temel ilişki	Önerilen sınama
Ö1	İhlal ve kasıt → hak edilmişlik → schadenfreude	Senaryo deneyi; ardışık aracılık; ahlaki kriz–performans krizi karşılaştırması
Ö2	Statü / özdeşleşmeme / rakip özdeşleşmesi → schadenfreude	Çok gruplu deney; kötü niyetli haset ve kimlik doğrulama ölçümleri
Ö3	Schadenfreude → intikam → NWOM / boykot / kaçınma	Boylamsal panel; paylaşım davranışı ve gerçek tıklama ölçümleri
Ö4	Platform pekiştirmesi × schadenfreude → kolektif yaptırım	Beğeni sayısı ve algoritmik görünürlük manipülasyonu; ağ analizi
Ö5	Schadenfreude → NWOM → yeniden satın alma / ödeme istekliliği	Teşvik uyumlu fiyat seçimi; CRM tekrar satın alma verisi; kriz yanıtı deneyi

5.3. Ampirik Sınama Tasarımı

Model, çok yöntemli bir araştırma programı gerektirir. İlk çalışma, kriz türünü (ahlaki ihlal–performans hatası), kasıt düzeyini ve marka statüsünü faktöriyel olarak manipüle eden bir senaryo deneyi olabilir. Hak edilmişlik, kötü niyetli haset, özdeşleşmeme, schadenfreude, öfke ve marka nefreti ayrı ölçeklerle ölçülmeli; yapılar doğrulayıcı faktör analiziyle ayrıştırılmalıdır. Özellikle schadenfreude ile öfkenin ayırt edici geçerliliği gösterilmeden önerilen mekanizmanın özgüllüğü savunulamaz.
İkinci çalışma platform pekiştirmesini sınayabilir. Aynı kriz içeriği düşük veya yüksek beğeni, yeniden paylaşım ve yorum normlarıyla sunularak katılımcının gerçek paylaşım, yorum seçimi ve görüntüleme süresi ölçülebilir. Beyan edilen NWOM niyeti yanında davranışsal veri kullanmak, sosyal beğenirlik yanlılığını azaltır. Ağ konumu, siyasi kimlik ve rakip marka özdeşleşmesi çok düzeyli modellerle incelenebilir.
Üçüncü çalışma ekonomik sonuçlara odaklanmalıdır. Katılımcılara gerçek veya teşvik uyumlu bütçe verilip hedef marka ile rakipler arasında fiyatlandırılmış seçim yaptırılabilir. Yeniden satın alma için müşteri ilişkileri yönetimi verisi veya dijital fiş panelleri, kriz öncesi ve sonrası dönemleri karşılaştırmak üzere farkların farkı tasarımıyla analiz edilebilir. Ödeme istekliliği açık artırma, seçim deneyi veya fiyat merdiveniyle ölçülmeli; salt satın alma niyetinden türetilmemelidir.
Dördüncü çalışma zamansal kalıcılığı test etmelidir. Krizden hemen sonra, bir ay sonra ve üç–altı ay sonra tekrarlanan ölçümler; schadenfreude'nin sönümlenmesini, NWOM yatırımının tutarlılık baskısını ve özür–düzeltici eylemin gecikmeli etkisini ayırabilir. Bu tasarım, "kalıcı düşüş" savını ampirik olarak sınar ve geri kazanımın hangi tüketici segmentlerinde mümkün olduğunu belirler.

5.4. Kuramsal Katkılar

Birinci katkı, marka krizi yazınındaki baskın olumsuz duygu yaklaşımını genişletmektir. Kriz mağduriyeti öfke ve üzüntü üretirken, marka kaybı bazı gözlemcilerde olumlu duygulanım yaratabilir. Schadenfreude'nin modele eklenmesi, neden doğrudan etkilenmeyen tüketicilerin krize yoğun biçimde katıldığını ve neden olumsuz haberin yayılmasının özünde ödüllendirici olabildiğini açıklar.
İkinci katkı, iptal kültürünü yalnızca tutum değişimi olarak değil, duygusal ödül ile platform pekiştirmesinin birleştiği kolektif yaptırım sistemi olarak kavramsallaştırmaktır. Sosyal ağlar ahlaki yargıyı görünür kılar, fakat aynı zamanda gloat etme ve grup statüsü kazanımını ödüllendirir. Bu çifte işlev, meşru hesap verebilirlik ile orantısız dijital linç arasındaki geçişin anlaşılmasına yardımcı olur.

Üçüncü katkı, schadenfreude ile ekonomik sonuçlar arasındaki açıklayıcı köprüyü kurmaktır. Duygu, intikam güdüsü ve negatif eWOM aracılığıyla güveni, sembolik faydayı ve fiyat primi gerekçesini aşındırır. Böylece yeniden satın alma niyeti ve ödeme istekliliği, kriz iletişiminin ikincil sonuçları değil, duygunun sosyal dolaşım biçimleri tarafından üretilen pazar çıktıları olarak ele alınır.
Dördüncü katkı, tamponların ikili doğasını göstermektir. Marka sevgisi, marka değeri ve topluluk bağlılığı bağışlamayı destekleyebilir; ancak paylaşılan kimliğin ihlali durumunda beklenti açığını büyüterek daha sert tepkiye yol açabilir. Bu nedenle ilişki gücü, evrensel bir koruyucu değişken yerine kriz–kimlik uyumuna bağlı koşullu bir kaynak olarak tanımlanır.

5.5. Yönetsel Çıkarımlar

Markalar ilk olarak kriz hacmini değil, duygusal mimarisini teşhis etmelidir. Öfke telafi ve yüzleşme talep ederken, schadenfreude markanın kaybını ödüllendirici bulur; utanç geri çekilmeyi, ihanet ise ilişkinin onarılmasını veya cezalandırılmasını tetikleyebilir. Sosyal dinleme sistemleri duygu etiketlerini mekanik olarak sınıflandırmak yerine hak edilmişlik, alay, rakip kimliği, mağdur sempatisi ve intikam dilini ayırt etmelidir.
İkinci olarak marka, kriz yanıtını kanıtlanabilir onarım sinyallerine bağlamalıdır. Özür sorumluluk kabulünü; düzeltici eylem ise tekrar riskinin azaltıldığını göstermelidir. Yanıtın zamanlaması önemlidir, fakat hız doğruluk ve mağdur tanımayı ikame etmemelidir. Alaycı veya küçümseyici kurumsal ton, özellikle marka savunucularının saldırgan yorumlarıyla birleştiğinde gözlemci sempatisini şikâyetçiye yöneltebilir. Topluluk yöneticileri savunuculara örtük olarak saldırganlık teşviki vermemelidir.
Üçüncü olarak yüksek statülü markalar görünür üstünlüğün kırılganlığını yönetmelidir. Gösterişçi ve kendini yücelten iletişim, başarısızlık anında haset ve hak edilmişlik değerlendirmesini büyütebilir. Toplumsal katkı mesajları yalnızca kriz anında ortaya çıkarsa stratejik makyaj olarak algılanabilir; uzun dönemli, doğrulanabilir ve iş modeliyle uyumlu davranışlar daha güçlü tampon oluşturur.
Dördüncü olarak fiyat indirimi kriz onarımının varsayılan aracı olmamalıdır. Ahlaki ihlalin yarattığı sembolik değer kaybı, parasal teşvikle kolayca giderilemez; bazı damgalanmış kimlik bağlamlarında indirim saygısızlık algısını dahi artırabilir (Du vd., 2025). Önce mağduriyetin tanınması ve kurumsal uygulamanın düzeltilmesi, sonra değer önerisinin yeniden kurulması gerekir.
Beşinci olarak başarı ölçümü yalnızca duygu tonuna veya paylaşım hacmine dayanmamalıdır. Sessiz gözlemcilerin satın alma davranışı, fiyat duyarlılığı, marka değiştirme, arama sonuçlarındaki kriz çağrışımları ve farklı segmentlerin geri kazanım hızı birlikte izlenmelidir. Kısa dönemde tartışma hacminin düşmesi, schadenfreude'nin veya ekonomik etkinin sona erdiğini göstermez.

5.6. Sınırlılıklar ve Gelecek Araştırmalar

Bu çalışmanın ilk sınırlılığı kavramsal niteliğidir. Önerilen ardışık aracılık ve düzenleyiciler, farklı kriz türleri ve kültürlerde ampirik olarak sınanmalıdır. İkinci sınırlılık, iptal kültürü ve dijital linç kavramlarının normatif yüklü olmasıdır. Gelecek çalışmalar eleştirinin meşruiyeti, kanıt gücü, orantılılık ve hedefin insan veya kurum oluşunu ayrı boyutlarda ölçmelidir.
Üçüncü sınırlılık, mevcut araştırmaların önemli bölümünün niyet ölçeklerine ve tek zamanlı tasarımlara dayanmasıdır. Gerçek paylaşım, satın alma, fiyat seçimi ve uzunlamasına davranış verisi modelin ekonomik iddialarını güçlendirecektir. Dördüncü olarak kültürel bağlam önemlidir. Değer krizleri kolektivist bağlamlarda, performans krizleri ise bireyci bağlamlarda farklı duygusal tepki üretebilir (Baghi & Gabrielli, 2019). Türkiye gibi yüksek bağlamsallık, güçlü grup aidiyeti ve yoğun platform kullanımının kesiştiği pazarlarda yerel ölçek uyarlamaları gereklidir.
Beşinci olarak yapay zekâ ve algoritmik sistemlerin kurumsal failiyet algısını nasıl değiştirdiği araştırılmalıdır. Tüketici, otomatik kararın hatasını insan hatasından daha az kasıtlı görebilir; fakat algoritmanın şeffaf olmaması veya tekrar eden ayrımcılık sistemik sorumluluk atfını artırabilir. Gelecek araştırmalar insan, algoritma ve insan–algoritma ortak kararlarını karşılaştırmalı; açıklanabilirlik ve gözetim sinyallerinin schadenfreude üzerindeki etkisini test etmelidir.

5.7. Sonuç

Dijital marka krizleri, kurumsal bir hatanın görünür olmasından daha fazlasıdır: kimlik, ahlak ve statü değerlendirmelerinin ağlar içinde kolektif yaptırıma dönüştüğü toplumsal olaylardır. Schadenfreude bu dönüşümde kritik bir geçiş mekanizmasıdır. Algılanan hak edilmişlik, haset ve özdeşleşmeme markanın kaybını psikolojik olarak ödüllendirici kılar; intikam güdüsü ve negatif eWOM bu ödülü davranışsal ve ekonomik zarara dönüştürür.

Bununla birlikte model, kaçınılmaz bir çöküş varsaymaz. Güçlü marka değeri, tutarlı sosyal sorumluluk, samimi özür ve doğrulanabilir düzeltici eylem olumsuz yolu zayıflatabilir; bazı kimlik uyumlu tüketiciler dış grup tepkisi karşısında markaya daha fazla destek verebilir. Akademik ve yönetsel mesele, krizin var olup olmamasından çok, hangi tüketicinin hangi değerlendirme üzerinden haz duyduğu, bu hazzın platformca nasıl pekiştirildiği ve ne zaman gerçek satın alma ile fiyat davranışına dönüştüğüdür. Sunulan önermeler, bu soruları deneysel, boylamsal ve davranışsal verilerle sınamak için bütünleşik bir araştırma gündemi sağlamaktadır.

Bu çerçevenin temel kuramsal sonucu, schadenfreude'nin marka krizleri ile pazar sonuçları arasında basit bir eşlik eden duygu değil, değerlendirmeyi davranışa taşıyan bir mekanizma olmasıdır. Tüketici markanın ihlalini kasıtlı, önlenebilir ve ahlaki açıdan ağır gördüğünde hak edilmişlik yargısı markanın kaybını uygun bir ceza olarak anlamlandırır. Yüksek statüye yönelik haset, tüketici–marka özdeşleşmemesi ve rakip marka kimliği bu yargıya göreli konum ve benlik doğrulama değeri ekler. Böylece doğrudan zarar görmeyen gözlemci de markanın düşüşünü ödüllendirici bulabilir. Bu özellik, schadenfreude'yi öfke, tiksinti ve marka nefretinden ayırarak dijital krize katılımın neden yalnızca mağduriyet deneyimine dayanmadığını açıklar.

Duygular arasındaki bu ayrım, kriz tepkilerinin doğru yorumlanması bakımından önemlidir. Öfke ihlalin giderilmesini veya faille yüzleşmeyi amaçlarken schadenfreude hedefin kaybına olumlu değer yükler. Marka nefreti hedefe ilişkin daha bütünsel ve kalıcı bir olumsuz değerlendirme, tiksinti ise uzaklaşma eğilimi yaratabilir. Bu duygular aynı kişide birlikte bulunsa da davranışa geçiş yolları farklıdır. Schadenfreude'nin özgül etkisi, cezalandırmayı yalnızca gerekli değil, haz verici hâle getirebilmesidir. Bu nedenle ampirik çalışmalarda schadenfreude, öfke, nefret, ihanet ve utançtan ayrı ölçülmeli; markanın kaybından duyulan memnuniyet ile ihlalin kendisine verilen olumsuz tepki birbirine karıştırılmamalıdır.

Dijital platformlar pasif hazzın kolektif cezalandırmaya dönüşmesini kolaylaştırır. Alaycı yorumlar, memeler, kısa videolar ve yeniden paylaşımlar schadenfreude'yi görünür bir gloat etme performansına çevirir. Beğeni, yorum ve paylaşım sayıları davranışın hem yaygınlığı hem de meşruluğu hakkında sosyal kanıt üretirken, yüksek etkileşimli içeriklerin algoritmik olarak öne çıkarılması aynı ihlal çerçevesini tekrar tekrar güçlendirir. Bu döngüde negatif elektronik ağızdan ağıza iletişim, uyarı ve bilgi paylaşımından markaya zarar vermeyi amaçlayan intikam davranışına kayabilir. Meşru hesap verebilirlik talebi ile orantısız dijital linç arasındaki sınır bu nedenle eleştirinin olumsuz olmasından çok kanıt kalitesi, hedef gösterme, tekrar ve yaptırımın ölçülülüğü üzerinden değerlendirilmelidir.

Ekonomik aşınma tek bir kanaldan gerçekleşmez. Hak edilmişlik yargısı krizi markanın karakteri hakkında tanısal bilgiye dönüştürdüğünde güven ve ilişki kalitesi zayıflar; tüketici aynı markayı yeniden seçmeyi yanlış davranışa rıza göstermek veya kendi kimliğiyle çelişmek olarak görebilir. Kriz aynı zamanda rakip seçeneklerin ahlaki ve sembolik üstünlüğünü görünür kılarak marka değiştirme davranışını teşvik eder. Yüksek statülü markalarda utanç ve ikiyüzlülük çağrışımları kalite, seçkinlik ve aidiyet için ödenen fiyat priminin dayanağını aşındırabilir. Negatif içeriğin arama sonuçları ve öneri sistemlerinde yeniden dolaşıma girmesi ise satın alma anında kriz belleğini etkinleştirerek kısa dönemli tepkinin daha uzun süreli kaçınmaya dönüşmesine katkı sağlar.

Bununla birlikte bu yollar bütün tüketiciler ve krizler için aynı güçte değildir. Öncül marka değeri, tutarlı sosyal sorumluluk ve güçlü ilişki yatırımı bağışlamayı destekleyebilir; fakat değer ihlali paylaşılan kimliğin merkezine dokunduğunda aynı bağlılık daha büyük bir ihanet ve utanç tepkisi yaratabilir. Rakip marka özdeşleşmesi, ideolojik uyum ve grup rekabeti markanın kaybını kimlik doğrulayan bir sonuca dönüştürürken, dış grubun öfkesi bazı destekçilerde öz–marka bağını daha da güçlendirebilir. Bu nedenle ortalama etki, birbirine ters segment sonuçlarını gizleyebilir. Kriz türü, hedefin statüsü, tüketicinin markayla ilişkisi ve platformdaki ağ konumu birlikte ele alınmadan schadenfreude'nin ekonomik sonuçları hakkında genelleme yapılmamalıdır.

Marka yönetimi açısından ilk görev kriz hacmini değil, krizin duygusal ve ahlaki mimarisini teşhis etmektir. Doğrudan mağdurların telafi beklentisi, hayal kırıklığı yaşayan sadık müşterilerin ihanet duygusu, rakip toplulukların hazzı ve fırsatçı yayıcıların görünürlük arayışı aynı yanıtla yönetilemez. Özür sorumluluk kabulünü, doğrulanabilir düzeltici eylem ise tekrar riskinin azaltıldığını göstermelidir; bu iki unsur birlikte sunulmadığında yanıt sembolik ve ikiyüzlü algılanabilir. Kurumsal veya savunucu toplulukların alaycı tonu şikâyetçiye yönelik gözlemci sempatisini artırabileceği için marka, saldırgan savunuculuğu teşvik etmemelidir. Ahlaki ve sembolik değer kaybı giderilmeden uygulanan fiyat indirimi de onarımın yerine geçmez ve bazı durumlarda saygısızlık algısını güçlendirebilir.

Modelin ampirik sınanması, beyan edilen niyetlerin ötesine geçen çok yöntemli bir tasarım gerektirir. Senaryo deneyleri kriz türü, kurumsal kasıt ve marka statüsünü değiştirerek hak edilmişlik, haset, özdeşleşmeme ve schadenfreude arasındaki ayrımı test edebilir. Platform deneylerinde beğeni, paylaşım ve yorum normları değiştirilerek sosyal pekiştirmenin gerçek paylaşım, görüntüleme süresi ve yorum seçimi üzerindeki etkisi ölçülebilir. Yeniden satın alma ve ödeme istekliliği ise yalnızca niyet ölçeğiyle değil, teşvik uyumlu fiyat seçimi, açık artırma, sepet verisi ve gerçek tekrar satın alma kayıtlarıyla değerlendirilmelidir. Boylamsal ölçümler schadenfreude'nin sönümlenmesini, kriz çağrışımının kalıcılığını ve özür–düzeltici eylemin gecikmeli etkisini birbirinden ayırabilir.

Sonuç olarak dijital marka krizlerinin ekonomik etkisi, olumsuz bilginin yayılmasından çok bu bilginin hangi duygusal ödülleri ve toplumsal konumları ürettiğine bağlıdır. Schadenfreude, markanın kaybını hak edilmiş ve tatmin edici gören değerlendirmeyi intikam, negatif elektronik ağızdan ağıza iletişim, boykot ve kaçınma davranışlarına bağlar. Platform pekiştirmesi bu geçişi hızlandırabilir; samimi sorumluluk kabulü, kanıtlanabilir onarım ve tutarlı kurumsal davranış ise hazzın meşruiyet temelini zayıflatabilir. Bu nedenle marka krizlerinin yönetimi yalnızca konuşma hacmini azaltmaya değil, mağduriyeti tanımaya, yanlış davranışı düzeltmeye ve sessiz gözlemciler dâhil farklı tüketici gruplarında güven ile sembolik değerin nasıl yeniden kurulacağını anlamaya yönelmelidir.

Kaynakça

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BİLGİ ASİMETRİSİ VE RİSK ALGISI BAĞLAMINDA GÜMÜŞ EKONOMİ TÜKETİCİLERİNİN SOSYAL TİCARET DAVRANIŞLARI

SOCIAL COMMERCE BEHAVIORS OF SILVER ECONOMY CONSUMERS IN THE CONTEXT OF INFORMATION ASYMMETRY AND RISK PERCEPTION

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Özet

Bu çalışma, 60 yaş ve üzeri tüketicilerin sosyal ticaret ekosistemindeki güven oluşumunu dijital kırılganlık ve dijital bağımsızlık arasındaki gerilim üzerinden açıklayan bütünleştirici bir kavramsal model geliştirmektedir. Sosyal medya ile çevrim içi ticaretin birleşmesi, ileri yaş tüketicilere daha geniş ürün erişimi, sosyal bağ ve gündelik yaşam kolaylığı sağlarken; satıcı kimliğinin belirsizliği, algoritmik yönlendirme, yanıltıcı tasarım örüntüleri ve çok katmanlı veri işleme süreçleri bilgi asimetrisini büyütebilmektedir. Çalışma, Teknoloji Kabul Modeli ve UTAUT2'yi sinyalleme teorisi, gizlilik hesabı, öz yeterlik yaklaşımı, sosyo-duygusal seçicilik ve dijital kırılganlık yazınıyla bir araya getirmektedir. Temel sav, güvenin tek başına yüksek olması gereken bir tutum değil, platform sinyallerinin doğrulanabilirliği ile tüketicinin risk ayırt etme kapasitesi arasında kalibre edilen dinamik bir karar kaynağı olduğudur. Bu çerçevede bilgi asimetrisi, bilişsel yük ve teknoloji kaygısının algılanan riski artırdığı; yaş dostu tasarım, dijital okuryazarlık, sosyal destek, şeffaflık ve etkili telafi mekanizmalarının ise öz yeterlik ile kalibre edilmiş güveni güçlendirdiği ileri sürülmektedir. Model, satın alma ve kullanım niyetini dijital bağımsızlığın yalnızca ara çıktıları olarak ele almakta; nihai sonucu, tüketicinin başkasına zorunlu bağımlılık duymadan güvenli, geri döndürülebilir ve bilgiye dayalı karar verebilmesi biçiminde tanımlamaktadır. Beş araştırma önermesi, güvenin aracılık rolünü, riskin koşullayıcı etkisini ve dijital okuryazarlığın doğrusal olmayan sonuçlarını ampirik sınamaya açmaktadır.

Anahtar Kelimeler: gümüş ekonomi, sosyal ticaret, dijital kırılganlık, ileri yaş tüketiciler, kalibre edilmiş güven, dijital bağımsızlık

Abstract

This study develops an integrative conceptual model explaining trust formation among consumers aged 60 and over in the social commerce ecosystem through the tension between digital vulnerability and digital independence. The convergence of social media and online commerce provides older consumers with broader product access, social connection, and everyday convenience, while uncertainty about seller identity, algorithmic steering, deceptive design patterns, and multilayered data-processing practices can intensify information asymmetry. The study integrates the Technology Acceptance Model and UTAUT2 with signaling theory, privacy calculus, self-efficacy, socioemotional selectivity, and the digital vulnerability literature. Its central argument is that trust is not an attitude that should simply be maximized, but a dynamic decision resource calibrated between the verifiability of platform signals and the consumer's capacity to distinguish risk. Within this framework, information asymmetry, cognitive load, and technology anxiety increase perceived risk, whereas age-friendly design, digital literacy, social support, transparency, and effective redress mechanisms strengthen self-efficacy and calibrated trust. The model treats purchase and use intentions only as intermediate outcomes of digital independence and defines the ultimate outcome as the consumer's ability to make safe, reversible, and informed decisions without compulsory dependence on others. Five research propositions make the mediating role of trust, the moderating effect of risk, and the nonlinear consequences of digital literacy open to empirical testing.

Keywords: silver economy, social commerce, digital vulnerability, older consumers, calibrated trust, digital independence

1. Giriş: Gümüş Ekonomi ve Yaşlanan Tüketicilerin Dijitalleşmesi

Nüfusun yaşlanması, tüketici pazarlarının büyüklüğünü ve değer üretme mantığını yeniden düzenlemektedir. Gümüş ekonomi, ileri yaş nüfusu yalnızca sağlık ve bakım harcamalarıyla tanımlanan bir maliyet kategorisi olmaktan çıkarır; gelir, deneyim, zaman ve ilişki sermayesi taşıyan heterojen bir tüketici alanı olarak ele alır. Bu dönüşüm dijital kanallarla hızlanmaktadır. Çevrim içi satın alma, mobil ödeme, sosyal medya temelli ürün keşfi ve dijital sağlık hizmetleri, yaşlanma deneyiminin gündelik tüketim boyutuna yerleşmiştir. Avrupa ülkelerinde 55-74 yaş grubunun çevrim içi satın alma düzeyi ile

kişi başına düşen gelir arasındaki pozitif ilişki ve Çin'de gümüş ekonominin büyüklüğüne ilişkin projeksiyonlar, dijital katılımın makroekonomik önemini görünür kılmaktadır (Meidute-Kavaliauskiene vd., 2026; Shao vd., 2025). Bununla birlikte bu ilişki nedensellik kanıtı değildir; daha yüksek gelir, daha iyi altyapı ve eğitim düzeyi hem çevrim içi alışverişi hem de ekonomik performansı birlikte açıklayabilir.

İleri yaş tüketicilerin dijitalleşmesini yaşa indirgemek analitik açıdan yetersizdir. Kronolojik yaş; eğitim, gelir, sağlık, yaşam düzeni, önceki mesleki teknoloji deneyimi ve sosyal destekle birlikte işleyen kaba bir göstergedir. "Genç yaşlı" olarak nitelenen 65-74 yaş grubu ile 75 yaş üzerindeki tüketicilerin fiziksel, bilişsel ve toplumsal kaynakları aynı değildir. Ayrıca kuşaklar arasındaki kullanım farklılıklarının önemli bir bölümü biyolojik yaşlanmadan çok teknolojilerle karşılaşma zamanına ve tarihsel deneyime bağlıdır (Nunan & Di Domenico, 2019; Franco, 2023). Bu nedenle yaşlı tüketiciyi yeniliğe kapalı, homojen ve yardıma muhtaç bir segment olarak kodlayan pazarlama uygulamaları hem açıklayıcı gücünü hem de etik meşruiyetini kaybeder.

Dijital benimseme yazını bu heterojenliği kısmen yakalar. Teknoloji Kabul Modeli, algılanan fayda ile algılanan kullanım kolaylığını kabulün temel bilişsel öncülleri olarak tanımlar (Davis, 1989). UTAUT ve tüketici bağlamına uyarlanmış UTAUT2 ise performans beklentisi, çaba beklentisi, sosyal etki, kolaylaştırıcı koşullar, hazcı motivasyon, fiyat değeri ve alışkanlığı aynı çerçevede birleştirir (Venkatesh vd., 2003; Venkatesh vd., 2012). Mobil alışveriş bulguları bu değişkenlerin yanına güven ve algılanan riski yerleştirir (Huang, 2023). İleri yaş gruplarında algılanan fayda güçlü bir açıklayıcı olmaya devam etmekte; teknoloji kaygısı, öz yeterlik ve sosyal destek bu ilişkinin gücünü belirlemektedir (An vd., 2024). Moxley vd. (2022) algılanan değerin teknoloji benimseme isteği üzerindeki etkisini $\beta = .54$, yaşam kalitesi artışı algısını $\beta = .24$ ve kullanım güvenini $\beta = .15$ olarak bildirmiştir. Schroeder vd. (2023) ise benimseme niyetiyle ilişkili 119 etmeni altı tema altında haritalamıştır. Bu bulgular, tek değişkenli "yaş etkisi" açıklamalarının yetersizliğini ortaya koyar.

Dijital okuryazarlık tüketim yapısını ve karar kalitesini etkileyen üretken bir kaynaktır. Li ve Shao (2025), dijital okuryazarlıktaki her birimlik artışın hanehalkı tüketim yapısındaki yükselişle ilişkili olduğunu ve mekanizmanın bilgi arama, fiyat karşılaştırma, akran değerlendirmelerine erişim, ruh sağlığı ve ihtiyati tasarruf üzerinden işlediğini göstermektedir. Yine de erişim ile yetkinlik özdeş değildir. Bir tüketicinin akıllı telefon sahibi olması, reklam ile kullanıcı içeriğini ayırt edebildiği, veri paylaşım sonuçlarını kavradığı ya da sosyal kanıtı doğrulayabildiği anlamına gelmez. Dijital katılımın niceliği arttıkça maruziyet de artabilir; dolayısıyla benimseme, koruyucu kapasite olmadan kırılganlığı azaltmayabilir.

Bu bildiri, ileri yaş tüketicinin sosyal ticaretteki güven sorununu benimseme niyetinin ötesine taşımaktadır. Araştırma sorusu şudur: Sosyal ticaret ortamlarında bilgi asimetrisi, bilişsel yük, platform sinyalleri ve sosyal destek hangi mekanizmalarla güveni biçimlendirir ve bu güven hangi koşullarda dijital bağımsızlığa dönüşür? Çalışma, 2011-2026 dönemindeki teknoloji kabulü, sosyal ticaret, çevrim içi dolandırıcılık, kullanılabilirlik ve dijital okuryazarlık bulgularını kuram bütünleştirici bir sentezle ilişkilendirir. Sistematik derleme ya da meta-analiz iddiası taşımaz; mevcut ampirik örüntülerden test edilebilir kavramsal ilişkiler türetir. Böylece katkı, "daha fazla güven daha fazla benimseme yaratır" önermesini ayrıştırarak güvenin kaynağını, doğrulanabilirliğini ve özerk karar verme üzerindeki sonucunu açıklamaktır.

2. Sosyal Ticaret ve Dijital Kırılganlık

2.1 Sosyal ticaretin platform mantığı

Sosyal ticaret, ürün arama, değerlendirme, tavsiye, satın alma ve satış sonrası etkileşimin sosyal ağların ilişki ve içerik altyapısı içinde gerçekleştiği ticari düzeni ifade eder. Geleneksel e-ticarette kullanıcı çoğunlukla belirli bir satın alma amacıyla platforma gelir; sosyal ticarette ise ticari uyarıcılar gündelik haber akışına, arkadaş ilişkilerine, canlı yayınlara ve içerik üreticilerinin anlatılarına gömülür. Değerlendirmeler, puanlar, topluluklar ve tavsiyeler belirsizliği azaltarak satın alma niyetini destekler (Hajli, 2015). Aynı bileşenler, ticari niyetin sosyal yakınlık görünümü altında belirsizleşmesine de yol açabilir. Platform, pazar yeri ve medya kurumu rollerini aynı anda üstlendiği için güvenin nesnesi satıcıdan ibaret değildir; ödeme altyapısı, içerik üreticisi, öneri algoritması ve kullanıcı topluluğu da güven ilişkisinin tarafları hâline gelir.

İleri yaş tüketiciler sosyal ticareti yalnızca işlevsel yarar üzerinden değerlendirmez. Aileyle bağlantıda kalma, kimliği sürdürme, emeklilikte yeni ilgi alanları geliştirme ve gündelik yaşamı kolaylaştırma

amaçları dijital katılımı besler (Franco, 2023). Sosyo-duygusal seçicilik yaklaşımı, zaman ufku daraldıkça duygusal açıdan anlamlı ve güvenli ilişkilerin öncelik kazanacağını öngörür. Bu nedenle sosyal varlık, tanıdık bir yüz, aile tavsiyesi veya müşteri hizmetlerine erişebilme hissi satın alma kararında belirleyici olabilir. Canlı yayın alışverişinde duygusal sosyal varlığın orta ve ileri yaş gruplarında güven ve algılanan fayda üzerinden satın alma niyetini güçlendirdiğine ilişkin bulgular bu mekanizmayla uyumludur (Jin vd., 2025).

Bununla birlikte sosyal kanıtın koruyucu etkisi koşulludur. Akran değerlendirmeleri bilgi asimetrisini azaltabilir; fakat sahte yorumlar, seçici görünürlük ve sponsorlu içeriğin belirsiz sunumu aynı sezgisel kestirme yollarını istismar eder. Güçlü bağlardan gelen öneriler doğrulama maliyetini düşürürken, yanlış bilginin güvenilir ilişki ağları içinde yayılmasını da kolaylaştırabilir (Hu vd., 2026). Dolayısıyla sosyal etki, UTAUT2'deki doğrusal ve çoğunlukla olumlu rolünden farklı olarak çift yönlü ele alınmalıdır. Etkinin sonucu, kaynağın uzmanlığına, çıkar ilişkisinin açıklığına ve tüketicinin çapraz doğrulama kapasitesine bağlıdır.

2.2 Dijital kırılganlığın çok boyutlu yapısı

Dijital kırılganlık, yalnızca düşük teknik beceri ya da dolandırıcılık mağduriyeti değildir. Bireyin bilişsel, ekonomik ve sosyal kaynakları ile platformun tasarım ve yönetişim özellikleri arasındaki uyumsuzluktan doğan ilişkisel bir durumdur. Sakariassen (2025) kavramı çok boyutlu biçimde ele alırken; Kemp ve Pérez (2023), yaşlı yetişkinlerin toplam dolandırıcılık prevalansında her zaman daha yüksek risk taşımadığını, ancak çevrim içi maruziyet kontrol edildiğinde bazı mağduriyet olasılıklarının artabildiğini belirtir. Bu ayrım önemlidir. Yaşı doğrudan risk nedeni olarak sunmak dijital yaş ayrımcılığını yeniden üretir; maruziyet, hedeflenme, koruyucu beceri ve sonuçların şiddetini birbirinden ayırmak ise müdahale tasarımını somutlaştırır.

Kırılganlık dört düzeyde işler. Birinci düzey bireyseldir: çalışma belleği, dikkat, duyusal kapasite, teknoloji kaygısı ve öz yeterlik karar sürecini etkiler. İkinci düzey ilişkiseldir: yalnızlık, aile desteğinin niteliği, akran ağları ve yardım isteme maliyeti önem taşır. Üçüncü düzey platform düzeyidir: arayüz karmaşıklığı, yanıltıcı tasarım, kimlik doğrulama yükü, reklam etiketlerinin görünürlüğü, tavsiye sistemlerinin opaklığı ve etkili itiraz yolları riski dağıtır. Dördüncü düzey kurumsaldır: tüketiciyi koruma rejimi, ödeme güvencesi, dolandırıcılık bildirimi, kırsal altyapı ve eğitim olanakları belirleyicidir. Bu katmanlar birbirini güçlendirebilir; örneğin teknoloji kaygısı düşük öz yeterliğe, düşük öz yeterlik yardım bağımlılığına, yardım bağımlılığı da mahremiyet kaybına yol açabilir.

Dolandırıcılar ve manipülatif tasarımlar bilişsel zayıflığı tek başına hedeflemez; otorite, aciliyet, kıtlık ve yakınlık sinyallerini birlikte kullanır. Teknik destek dolandırıcılığında kurumsal otorite taklidi; sağlık ürünlerinde yaşlanmayı yavaşlatma vaadi; romantik ve yatırım dolandırıcılığında ise duygusal bağ ve kayıp korkusu öne çıkar (Chen vd., 2025; Oka vd., 2025; Shapiro, 2025). Pehlivanoglu vd. (2024) ileri yaş, daha düşük bilişsel performans ve APOE4 genotipinin kimlik avı kırılganlığını birlikte artırabildiğini göstermektedir. Bu tür bulgular nüfus düzeyinde tarama ya da ayrımcı profil çıkarma için değil, güvenlik tasarımının bilişsel çeşitliliği hesaba katması için kullanılmalıdır.

Algoritmik özerklik, kullanıcının tercihlerini belirleme sürecinde öneri sistemlerinin görünmez etkisi karşısında amaç kurabilme, seçenekleri karşılaştırabilme ve öneriyi reddedebilme kapasitesidir. Sosyal ticarette kişiselleştirme, arama maliyetini azaltırken seçenek mimarisini de daraltır. Yaşlı kullanıcıların veri kümelerinde yetersiz temsil edilmesi, sistemlerin onların ihtiyaçlarını yanlış tahmin etmesine ve dijital yaş ayrımcılığını otomatikleştirmesine yol açabilir (Zhou vd., 2025). Bağımlılık yaratan tasarımların yalnızca gençleri hedefleyen bir düzenleme sorunu olarak ele alınması da ileri yaşta yalnızlık ve kompulsif kullanım risklerini görünmez bırakır (Yao, 2025). Dijital kırılganlık bu nedenle "kullanamama" kadar, kullanırken seçim alanının ve denetimin fark edilmeden aşınmasını da kapsar.

3. İleri Yaş Tüketicilerde Bilgi Asimetrisi ve Bilişsel Engeller

3.1 Bilgi asimetrisi ve sinyallerin yorumlanması

Bilgi asimetrisi, satıcı veya platformun ürün kalitesi, ticari niyet, veri kullanımı ve işlem güvenliği hakkında tüketiciden daha fazla bilgiye sahip olduğu durumu ifade eder. Sosyal ticarette asimetri, üçüncü taraf satıcılar ve kullanıcı üretimli içerik nedeniyle katmanlaşır. Tüketici çoğu zaman hangi içeriğin reklam olduğunu, yorumların gerçek deneyime dayanıp dayanmadığını, platformun öneriyi hangi verilerle ürettiğini ve uyuşmazlıkta hangi kurumun sorumlu olduğunu aynı anda değerlendirmek zorundadır. Sinyalleme teorisi, daha bilgili tarafın gözlemlenebilir göstergeler yoluyla kalite hakkında

işaret gönderdiğini öne sürer (Spence, 1978). Doğrulanmış satıcı rozeti, açık iade politikası, bağımsız ödeme güvencesi ve izlenebilir kullanıcı yorumu bu bağlamda sinyal işlevi görebilir. Ancak düşük maliyetle taklit edilebilen logolar ve rozetler ayırt edici değildir; görünürlükleri yüksek olsa da bilgi değerleri düşük olabilir.

İleri yaş kullanıcılar çevrim içi güvenilirliği değerlendirirken işletmeci kimliği, kurum logosu ve sayfa sahipliği gibi kaynak işaretlerine içerik ayrıntılarından daha fazla ağırlık verebilmektedir (Choi, 2020). Bu strateji her zaman irrasyonel değildir. İşleme kapasitesi sınırlı olduğunda güvenilir kurumsal sinyaller arama maliyetini düşürür. Sorun, platformun sinyal üretimini denetlememesi veya ticari aktörlerin kurumsal görünümü kolayca taklit edebilmesidir. Guo vd. (2025), çevrim içi sağlık topluluklarında sinyallerin etkisinin sağlık okuryazarlığına bağlı olduğunu göstermektedir. Aynı rozet, alan bilgisi yüksek bir kullanıcı için tamamlayıcı kanıt; düşük okuryazarlık düzeyindeki kullanıcı için ise sorgulanmayan otorite işareti olabilir.

Platform şeffaflığı asimetriyi bütünüyle ortadan kaldırmaz, fakat tüketicinin belirsizliğin kaynağını görmesini sağlar. Satıcı kimliği, sponsorlu içerik, veri kullanımı, yorum doğrulama yöntemi, toplam fiyat ve telafi süreci açık biçimde sunulduğunda ürün seçimi olasılığı ve prosedürel güven artabilir (Veltri vd., 2023; Culnan & Armstrong, 1999). Şeffaflık, uzun ve hukuki metinler yayımlamak değildir. Bilginin doğru anda, anlaşılır dilde, kıyaslanabilir biçimde ve eylemle ilişkili sunulması gerekir. Aksi hâlde açıklama yükümlülüğü, bilgi yükünü artırarak paradoksal biçimde asimetriyi derinleştirir.

3.2 Bilişsel yük bilgi kaçınması ve sezgisel karar

Çevrim içi ürün seçimi çok nitelikli karşılaştırma, geçici bilgi saklama ve görevler arasında geçiş gerektirir. Yaşla birlikte çalışma belleği ve işleme hızındaki değişimler, özellikle karmaşık karşılaştırma tablolarında karar doğruluğunu azaltabilir. Rydzewska vd. (2024), zor e-ticaret görevlerinde ileri yaş katılımcıların doğruluk oranının yüzde 90'dan yüzde 30'a kadar düşebildiğini ve görsel çalışma belleğinin yaş ile karar doğruluğu arasındaki ilişkiye aracılık ettiğini bildirmiştir. İnternet kullanımına ilişkin boylamsal bulgular da sözel bellek ve gecikmeli hatırlama performansının kullanmama olasılığıyla ilişkili olduğunu göstermektedir (Heponiemi vd., 2023). Bu sonuçlar bilişsel gerilemeyi tüm yaşlılara genelleştirmeyi değil, arayüzün bellek yükünü azaltacak biçimde tasarlanmasını gerektirir.

Bilgi bolluğu, bilgi eşitliği yaratmaz. Çok sayıda ürün, açılır pencere, kampanya sayacı, kimlik doğrulama adımı ve teknik terim tüketicinin işlem kapasitesini aşabilir. Bu durumda kullanıcı aramayı erken sonlandırabilir, varsayılan seçeneğe yönelebilir veya tanıdık bir logoya aşırı ağırlık verebilir. Deng vd. (2023), yaşın tüketici seçiminde bilgi kaçınmasıyla ilişkili olduğunu ve ileri yaş yetişkinlerin karar öncesinde daha az bilgi arayabildiğini göstermektedir. Bilgi kaçınması bazen öz koruma stratejisidir: kullanıcı kaygıyı ve zihinsel maliyeti azaltır. Fakat platformun sıralama ve varsayılanları ticari çıkarla biçimlendirdiği koşullarda bu strateji kullanıcıyı manipülasyona açık hâle getirir.

Kullanılabilirlik sorunları bilişsel kaynakları ürün değerlendirmesinden arayüz çözümlemeye aktarır. Küçük yazı, belirsiz simge, derin menü, çok adımlı doğrulama, sürekli güncelleme ve sistem durumunun görünmemesi hata olasılığını yükseltir (Li & Luximon, 2020; Khan vd., 2026). Mobil bankacılık uygulamalarında saptanan çok sayıdaki kullanılabilirlik sorunu, hata önleme ve sistem durumunun görünürlüğünün ileri yaş kullanıcılar için kritik olduğunu göstermektedir (Amouzadeh vd., 2026). Wang vd. (2026) düz gezinme yapılarının ağaç biçimli yapılara göre daha yüksek güven üretebildiğini, yapısal sadeliğin renk ipuçlarından daha önemli olduğunu raporlamıştır. Böylece "yaş dostu tasarım" estetik bir tercih değil, güven sinyalinin anlaşılabilirliğini belirleyen karar altyapısıdır.

Yanıltıcı tasarım örüntüleri, kullanıcının bilişsel kestirmelerini platform çıkarına yönlendirir. Önceden işaretlenmiş seçenekler, sahte kıtlık, abonelikten çıkmayı zorlaştırma, toplam fiyatı geç gösterme ve düğmeler arasında görsel dengesizlik bu kapsamdadır. Aung vd. (2024), ileri yaş kullanıcıların bu örüntüleri algıladığını, ancak hedefe yönelik eğitim ve koruyucu tasarım eksikliği yaşadığını göstermektedir. Bu noktada sorun bireysel dikkatsizlik değildir; tasarımcının davranışsal öngörü üstünlüğü ile kullanıcının sınırlı zamanı arasındaki asimetridir. Etik değerlendirme, kullanıcının işlemi tamamlayıp tamamlamadığına değil, kararın anlaşılan, geri alınabilir ve baskıdan uzak olup olmadığına odaklanmalıdır.

3.3 Kırılganlık yerine kapasite uyumu

İleri yaş tüketicilerin bilişsel ve fiziksel özelliklerini yalnızca eksiklik diliyle açıklamak stereotip tehdidi yaratabilir. Kişiselleştirilmiş önerilerin yeniliği bazı yaşlı tüketicilerde "teknolojiye uyumsuz" görülme kaygısını artırırken yenilikçi ürüne açıklığı da yükseltebilmektedir (Zhao & Fu, 2024). Dolayısıyla

tasarım, kullanıcı adına seçenekleri azaltmak yerine bilişsel yükü yönetmeli; ayrıntıyı katmanlı sunmalı, karşılaştırmayı kalıcılaştırmalı ve geri dönüş olanağı sağlamalıdır. Kapasite uyumu yaklaşımı, bireyin görevi yerine getirmek için ihtiyaç duyduğu bilişsel ve sosyal kaynaklarla sistemin talep ettiği kaynakların dengelenmesini ifade eder. Bu denge, dijital bağımsızlığın ön koşuludur.

Tablo 1 Kavramsal modelin temel yapıları ve ölçülebilir karşılıkları

Yapı	Kavramsal tanım	Sosyal ticarette mekanizma	Olası göstergeler
Bilgi asimetrisi	Platform ve satıcının tüketiciden daha fazla veya daha nitelikli bilgiye sahip olması	Kaynak, sponsorluk, veri kullanımı ve telafi sorumluluğunun belirsizleşmesi	Kaynak tanıma, fiyat şeffaflığı, sorumluluk algısı
Bilişsel yük	Görevin çalışma belleği ve dikkat kaynaklarına bindirdiği toplam talep	Derin menü, çoklu doğrulama, aşırı seçenek ve teknik dil	Görev süresi, hata sayısı, öznel yük
Teknoloji kaygısı	Dijital görev sırasında hata, kayıp veya yetersizlik beklentisi	İşlemi erteleme, çevrim dışına dönme, yardım bağımlılığı	Kaygı ölçeği, kaçınma, terk oranı
Algılanan risk	İşlemin olumsuz sonuçlarının olasılığı ve ciddiyetine ilişkin değerlendirme	Finansal kayıp, mahremiyet ihlali, performans ve yasal belirsizlik	Risk boyutları, ödeme isteği, veri açıklama niyeti
Kalibre edilmiş güven	Güven düzeyinin doğrulanabilir kanıt ve gerçek riskle uyumlu olması	Sinyalleri çapraz doğrulama ve gerektiğinde işlemi durdurma	Güven doğruluğu, sahte sinyal ayrımı, doğrulama davranışı
Dijital öz yeterlik	Belirli bir dijital görevi başarabileceğine ilişkin inanç	Bağımsız arama, karşılaştırma, ödeme ve sorun çözme	Görev özgü öz yeterlik, yardım sıklığı
Dijital bağımsızlık	Güvenli ve bilgiye dayalı dijital kararı zorunlu vekâlet olmadan verebilme	Satın alma, iptal, itiraz ve gizlilik tercihlerini yönetebilme	Bağımsız tamamlama, geri alma, telafiye erişim

4. Güven İnşası ve Dijital Bağımsızlık: Algılanan Risklerin Azaltılması

4.1 Güvenin nesnesi ve güvenin kalibrasyonu

Güven, bir aktörün belirsizlik altında karşı tarafın yetkin, dürüst ve iyi niyetli davranacağı beklentisiyle kırılganlığı kabul etmesidir. Sosyal ticarette bu beklenti çoklu nesnelere yönelir: satıcının ürünü doğru tanıtacağına, platformun sahte içeriği denetleyeceğine, ödeme sağlayıcının finansal veriyi koruyacağına ve topluluğun deneyimlerini dürüstçe paylaşacağına duyulan güven birbirinden ayrılmalıdır. Tek bir genel güven ölçeği bu farklı sorumlulukları örter. Acikgoz vd. (2024), mobil sosyal ticarette bilgi benimsemesinin güven üzerinden satın alma, sürdürme ve deneyim paylaşma niyetine taşındığını göstermektedir. Bu aracılık, güvenin niyete yakın bir belirleyici olduğunu; ancak güvenin hangi kanıta dayandığının ayrıca ölçülmesi gerektiğini düşündürür.

Kalibre edilmiş güven, güven düzeyi ile sistemin gerçek güvenilirliği arasındaki uyumdur. Eksik güven faydalı hizmetlerden dışlanmaya, aşırı güven ise dolandırıcılık ve mahremiyet kaybına yol açar. İleri yaş tüketiciler için amaç güveni koşulsuz yükseltmek değildir. Amaç, güvenilir sinyalleri tanıyabilme, sahte sinyalleri sorgulama ve belirsizlik yükseldiğinde işlemi durdurabilme kapasitesidir. Vivion vd. (2026), yaşlı yetişkinlerin bilgi kaynakları arasında güveni sürekli müzakere ettiğini ve sosyal medyaya yönelik refleksif güvensizliğin bilgi dayanıklılığı işlevi görebildiğini belirtmektedir. Bu bulgu, ileri yaş tüketiciyi pasif ve saf kabul eden yaklaşımlara karşı güçlü bir düzeltmedir.

Sinyallerin güven üretmesi için üç koşul gerekir. İlk olarak sinyal maliyetli veya doğrulanabilir olmalıdır; kolayca kopyalanabilen bir rozet zayıf sinyaldir. İkinci olarak sinyali veren aktör ile denetleyen aktör ayrılmalıdır; platformun kendi satıcısını kendi ölçütleriyle "güvenilir" ilan etmesi çıkar çatışması yaratabilir. Üçüncü olarak sinyal, karar anında anlaşılır olmalıdır. Uzun gizlilik metinleri yerine veri türü, kullanım amacı, saklama süresi ve silme seçeneğini katmanlı biçimde gösteren açıklamalar daha işlevselidir. Güven mimarisi, yalnızca güvenlik özelliği eklemek değil, sorumluluğu ve başvuru yolunu görünür kılmaktır.

4.2 Gizlilik hesabı ve risk boyutları

Gizlilik hesabı, tüketicinin veri açıklamanın beklenen yararlarını olası gizlilik kayıplarıyla karşılaştırdığı karar mantığını ifade eder. E-ticaret araştırmaları, gizlilik endişesinin işlem niyetini azalttığını; internet güveni ve algılanan yararın bu etkiyi dengeleyebildiğini göstermektedir (Dinev & Hart, 2006). Prosedürel adalet ve adil bilgi uygulamaları, tüketicinin kişisel verinin kullanımını kabul etmesinde kişisel olmayan güveni destekler (Culnan & Armstrong, 1999). İleri yaş bağlamında bu hesap salt olasılık çarpı sonuç işlemi değildir. Teknik terimlerin anlaşılmaması, veri akışının görünmezliği ve yardım için aile üyeleriyle parola paylaşma zorunluluğu, tüketicinin hem risk bilgisini hem de tercih özgürlüğünü sınırlar.

Algılanan risk çok boyutludur. Finansal risk para kaybını; performans riski ürün veya hizmetin vaat edileni vermemesini; gizlilik riski verinin amaç dışı kullanılmasını; yasal risk ise itiraz ve sorumluluk yollarının belirsizliğini ifade eder. Mobil ödeme araştırmaları finansal ve performans riskinin özellikle önemli olduğunu, mobil sağlıkta performans, gizlilik ve yasal risklerin öne çıktığını göstermektedir (Klaver vd., 2021; Yang vd., 2023). Bazı çalışmalarda gizlilik riskinin sürdürme niyeti üzerindeki etkisinin anlamsızlaşması, gizliliğin önemsiz olduğunu göstermez. Riskin etkisi güven, alışkanlık, kullanım bağlamı ve veri duyarlılığı üzerinden dolaylı işleyebilir. Ayrıca yaşlı kullanıcılar düşük gizlilik endişesi bildirdiklerinde bu durum gerçek riskin düşük algılanmasından veya kavramın soyut kalmasından kaynaklanabilir.

Risk azaltma, kullanıcının sorumluluğunu artırmakla sınırlı tutulamaz. Güvenli varsayılanlar, işlem öncesi toplam fiyat, güçlü fakat anlaşılır kimlik doğrulama, şüpheli transferlerde geri dönüş süresi, doğrulanmış satıcı kimliği, kolay iptal, erişilebilir müşteri hizmeti ve açık şikâyet izleme, riski kurumsal olarak paylaşır. Platformun yalnızca uyarı göstermesi, uyarıların sıklığı ve karmaşıklığı nedeniyle "uyarı yorgunluğu" yaratabilir. Etkili tasarım, yüksek riskli anda az sayıda eyleme dönük bilgi verir ve hatanın telafi edilebilirliğini artırır.

4.3 Dijital okuryazarlık sosyal destek ve öz yeterlik

Dijital okuryazarlık, cihaz kullanma becerisinden daha geniştir. Kaynak değerlendirme, ticari niyeti tanıma, veri izini kavrama, güvenlik ayarlarını yönetme, dolandırıcılık işaretlerini ayırt etme ve sorun durumunda telafi yoluna erişme yetkinliklerini içerir. Bir defalık genel eğitimler kısa süreli beceri kazandırabilir; kalıcılık, eğitimin kullanıcının gerçek hedeflerine ve kullandığı cihaza bağlanmasına bağlıdır. Evde, bire bir, uygulamalı ve kuşaklar arası programların daha etkili olduğuna ilişkin bulgular; aşamalı öğretim ve sürekli desteğin önemini göstermektedir (Ngiam vd., 2022; Choudhary & Bansal, 2022; Aleti vd., 2024). Moore ve Hancock (2022) yaşlı yetişkinlere yönelik dijital medya okuryazarlığı müdahalesinin yanlış habere karşı dayanıklılığı artırabildiğini göstermiştir.

Öz yeterlik, bireyin belirli bir görevi başarıyla yapabileceğine ilişkin inancıdır (Bandura, 1997). İleri yaşta öz yeterlik, algılanan kullanım kolaylığından daha kalıcı bir kaynak olabilir; çünkü kullanıcı yeni bir arayüzle karşılaştığında önceki ustalık deneyimlerini genelleyebilir. Görsel gösterim, akranın başarı örneği, küçük ve geri alınabilir görevler ile açık hata geribildirimi öz yeterliği besler. Buna karşılık yardımın sürekli olarak görevi kullanıcı adına tamamlaması, kısa vadede işlemi çözerken uzun vadede öğrenme fırsatını ortadan kaldırabilir. Dijital bağımsızlık, yardımın yokluğu değil, yardımın kapasite devri yaratacak biçimde düzenlenmesidir.

Sosyal destek aynı zamanda "toplumsal koruyuculuk" işlevi görür. Aile üyeleri riskli işlemi fark edebilir, bilgi kaynağını doğrulayabilir ve kayıp büyümeden müdahale edebilir (Chen vd., 2025). Kuşaklar arası desteğin algılanan kolaylık, fayda ve güven üzerinden çevrim içi hizmet niyetini güçlendirmesi bu işlevle uyumludur (Jin & Qu, 2025). Ancak koruyuculuk paternalizme dönüşmemelidir. Parolaların devri, kullanıcının hesap kontrolünü kaybetmesi veya tüm işlemlerin çocuklar tarafından yapılması bağımsızlığı azaltır. Tasarımın paylaşılabilir işlem önizlemesi, sınırlı yetkili yardımcı hesabı ve kullanıcı tarafından geri alınabilir onay gibi özellikler sunması, destek ile özerklik arasındaki dengeyi güçlendirebilir.

Okuryazarlığın etkisi her zaman doğrusal değildir. Daha fazla dijital beceri maruziyeti ve yabancılarla etkileşimi artırabilir; risk ayırt etme eğitimi eşlik etmediğinde aşırı güven doğabilir (Gao vd., 2026). Bu nedenle model, genel dijital akıcılık ile eleştirel güvenlik okuryazarlığını ayırır. İlki işlemi hızlandırır; ikincisi kaynağı, teşviki ve telafi edilebilirliği sorgular. Dijital bağımsızlık ancak iki kapasite birlikte geliştiğinde güçlenir.

5. Kavramsal Model ve Gelecek Araştırmalar

5.1 Bütünleştirici model

Önerilen model üç girdi kümesini iki risk mekanizması ve bir güven mekanizması üzerinden dijital bağımsızlığa bağlar. Yapısal ve tasarımsal maruziyetler bilgi asimetrisi, arayüz karmaşıklığı, yanıltıcı tasarım ve algoritmik opaklıktan oluşur. Bireysel kaynaklar dijital okuryazarlık, görev özgü öz yeterlik ve önceki deneyimi içerir. Sosyal ve kurumsal güvenceler ise aile ve akran desteği, doğrulanabilir platform sinyalleri, şeffaflık, güvenli varsayılanlar ve telafi mekanizmalarıdır. Yapısal maruziyetler algılanan riski ve teknoloji kaygısını yükseltirken, bireysel kaynaklar kaygıyı azaltır ve kalibre edilmiş güveni destekler. Sosyal ve kurumsal güvenceler güveni artırır; ancak sinyaller doğrulanabilir değilse yalnızca güven görünümü üretir.

Kabul ve kullanım niyeti modelde ara sonuçtur. Bir tüketici bir platformu kullanabilir, fakat işlemi kendi hedefleri doğrultusunda değerlendiremiyor, iptal edemiyor veya sorun durumunda başvuru yolunu kullanamıyorsa dijital bağımsızlık gerçekleşmemiştir. Bu nedenle sonuç değişkeni; bağımsız görev tamamlama, doğrulama davranışı, geri alma kapasitesi ve güvenli yardım kullanımıyla ölçülmelidir. Yaş grubu içi heterojenlik, ürün kategorisi ve kullanım bağlamı tüm yolları koşullandıran üst düzey değişkenlerdir. Sağlık ürünü, yatırım, günlük tüketim ve seyahat satın alımları aynı risk ağırlıklarına sahip değildir.



Şekil 1 İleri yaş tüketicilerde kalibre edilmiş güven ve dijital bağımsızlık modeli

5.2 Araştırma önermeleri

Modeldeki ilişkiler, mevcut bulguların yönü ile teorik mekanizmaların birlikte değerlendirilmesinden türetilmiştir. Önermeler yaşın doğrudan ve evrensel etkisini varsaymaz; görev, platform ve kaynak düzeyindeki koşulları sınamaya açar.

Önerme 1. *Sosyal ticarette algılanan bilgi asimetrisi, ileri yaş tüketicilerin algıladığı finansal, gizlilik, performans ve yasal riski artırır; bu ilişki arayüz karmaşıklığı ve algoritmik opaklık yükseldikçe güçlenir.*
Önerme 2. *Bilişsel yükün sosyal ticaret kullanım ve satın alma niyeti üzerindeki negatif etkisine teknoloji kaygısı aracılık eder; yaş dostu arayüz ve kolaylaştırıcı koşullar bu dolaylı etkiyi zayıflatır.*
Önerme 3. *Doğrulanabilir platform sinyalleri, prosedürel şeffaflık ve etkili telafi mekanizmaları kalibre edilmiş güveni artırır; kalibre edilmiş güven, algılanan fayda ile kullanım ve satın alma niyeti arasındaki ilişkiye pozitif yönde aracılık eder.*
Önerme 4. *Aile ve akran desteği, görev özgü öz yeterlik üzerinden dijital bağımsızlığı artırır; desteğin görevi kullanıcı adına devraldığı paternalist biçimlerde bu pozitif etki zayıflar ve yardım bağımlılığı artar.*
Önerme 5. *Genel dijital akıcılık ile dijital bağımsızlık arasındaki ilişki, eleştirel güvenlik okuryazarlığı tarafından koşullandırılır: güvenlik okuryazarlığı düşükken artan akıcılık maruziyet ve aşırı güven yoluyla kırılganlığı artırabilir; yüksekken doğrulama davranışı ve kalibre edilmiş güven yoluyla bağımsızlığı güçlendirir.*

5.3 Ampirik sınama ve ölçüm gündemi

Önermelerin sınanması için kesitsel niyet araştırmaları tek başına yeterli değildir. Güven, risk ve bağımsızlık zaman içinde değiştiği için boylamsal ve görev temelli tasarımlar gereklidir. İlk aşamada 60-69, 70-79 ve 80 yaş üzeri katmanları; eğitim, gelir, sağlık, yalnız yaşama ve önceki teknoloji deneyimiyle birlikte örneklemek uygun olacaktır. Kronolojik yaş sürekli değişken olarak korunmalı, segmentler yalnızca etkileşimleri yorumlamak için kullanılmalıdır. Yapısal eşitlik modeli, bilgi asimetrisi ile niyet arasındaki çoklu aracılık yollarını test edebilir; ancak öz bildirimlerin yanına gerçek görev performansı ve davranışsal kayıtlar eklenmelidir.
Deneysel çalışmalar, sinyal kalitesi ile arayüz yükünü bağımsız olarak manipüle edebilir. Örneğin doğrulanmış satıcı rozeti, bağımsız denetim açıklaması ve kolay iade güvencesi farklı kombinasyonlarda sunulabilir; katılımcının güven puanı kadar rozetin sahte olduğu denemelerde hatalı güveni de ölçülebilir. Böylece yüksek güven ile doğru güven ayrılır. Göz izleme, gezinme derinliği ve kritik bilginin fark edilme süresini; düşünme-aloud protokolü ise kullanıcıların hangi sezgisel işaretleri kullandığını gösterebilir. Dolandırıcılık simülasyonları etik olarak sınırlı kayıp, açık bilgilendirme ve kapsamlı çözümleme gerektirir.
Dijital bağımsızlık için çok boyutlu bir ölçek geliştirilmelidir. Alt boyutlar görev tamamlama, bilgi doğrulama, gizlilik tercihi, hata telafisi, yardımın kontrolü ve algoritmik özerklik olabilir. Ölçek, yalnızca "yardım almadan yapabilirim" maddelerine dayanmamalıdır; güvenli biçimde yardım istemek de bağımsızlığın parçasıdır. Ölçüm değişmezliği, yaş alt grupları, cinsiyet, eğitim ve kültürel bağlam arasında test edilmelidir. Türkiye'de aile desteğinin yüksekliği koruyucu olabilir; fakat hesap ve parola devrini normalleştirerek mahremiyet ve özerklik maliyeti de yaratabilir. Bu olasılık nitel görüşmeler ve hane içi görev gözlemleriyle incelenmelidir.

Tablo 2 Kavramsal önermeler için önerilen ampirik araştırma tasarımları

Araştırma alanı	Önerilen tasarım	Temel karşılaştırma	Başlıca çıktı
Sinyal kalibrasyonu	Faktöriyel çevrim içi deney	Doğrulanabilir sinyal × sahte sinyal × sinyalsiz koşul	Doğru güven, satın alma, doğrulama
Arayüz ve bilişsel yük	Laboratuvar görevi ve göz izleme	Düz gezinme × derin gezinme; düşük × yüksek seçenek sayısı	Hata, süre, terk, öznel yük
Dijital eğitim	Boylamsal saha deneyi	Genel beceri × güvenlik okuryazarlığı × birleşik program	Kalıcılık, maruziyet, bağımsızlık

Araştırma alanı	Önerilen tasarım	Temel karşılaştırma	Başlıca çıktı
Sosyal destek	Hane içi günlük ve görüşme	Öğretici destek × görevi devralan destek	Öz yeterlik, mahremiyet, yardım bağımlılığı
Platform yönetişimi	Doğal deney veya politika değerlendirmesi	Telafi ve şeffaflık değişikliği öncesi ve sonrası	Şikâyet, kayıp, sürdürme, güven

5.4 Kuramsal katkılar

Modelin ilk katkısı teknoloji kabulünü kırılganlık ve özerklik ölçütleriyle genişletmesidir. TAM ve UTAUT2 çoğunlukla kullanım niyeti ile fiilî kullanımı başarı çıktısı olarak görür. Oysa sosyal ticarette kullanım, manipülasyon veya yardım bağımlılığıyla birlikte gerçekleşebilir. Dijital bağımsızlığın sonuç değişkeni olarak eklenmesi, kabulün niteliğini değerlendirmeyi mümkün kılar.

İkinci katkı, güveni doğrusal bir kolaylaştırıcı olmaktan çıkarıp kalibrasyon problemi olarak tanımlamaktır. Sinyalleme teorisi güvenin hangi göstergelerden üretildiğini, gizlilik hesabı risk ve yarar dengesini, öz yeterlik ise kullanıcının bu dengeyi kurma kapasitesini açıklar. Bu üç yaklaşım bir araya geldiğinde hem güvensizlikten kaynaklanan dışlanma hem de aşırı güvenden kaynaklanan mağduriyet aynı model içinde incelenebilir.

Üçüncü katkı, dijital kırılganlığı bireysel eksiklikten platform sorumluluğuna doğru yeniden dağıtmaktır. Bilgi asimetrisi, karanlık örüntüler ve algoritmik opaklık kullanıcı özelliği değildir; tasarlanmış piyasa koşullarıdır. Bu nedenle dijital okuryazarlık tek çözüm olarak sunulamaz. Korumayı bireye devreden yaklaşım, platformun daha iyi bilgi ve davranışsal öngörüye sahip olmasından doğan sorumluluğunu gizler.

5.5 Yönetsel ve kamusal politika çıkarımları

Platform yöneticileri ileri yaş tüketiciler için ayrı ve küçültülmüş bir deneyim tasarlamak yerine evrensel tasarım ilkelerini uygulamalıdır. Okunabilir tipografi, düz gezinme, toplam fiyatın erken görünmesi, açık reklam etiketi, satıcı kimliğinin doğrulanması, geri alınabilir işlem ve erişilebilir insan desteği bütün kullanıcılar için faydalıdır. Güven ölçümü yalnızca dönüşüm oranına dayanmamalı; yanlış satın alma, iptal başarısı, şikâyetin çözülme süresi ve yüksek riskli işlemlerde doğrulama davranışı da izlenmelidir. Pazarlama iletişimi, yaşa dayalı korku ve yetersizlik imgelerinden kaçınmalıdır. Gerontografik segmentasyon kronolojik yaşın yanına yaşam evresi, sağlık, teknoloji deneyimi, değerler ve sosyal destek düzeyini koyar (Kannan vd., 2026). Güven sinyalleri marka iddiası olarak değil, bağımsız doğrulama ve açık sorumlulukla desteklenmelidir. Sosyal kanıt gösterilirken yorumun satın alma doğrulaması, sponsorlu ilişki ve sıralama ölçütü anlaşılır biçimde açıklanmalıdır.

Kamu politikası bireysel eğitim ile yapısal korumayı birlikte ele almalıdır. Toplum merkezleri, belediyeler ve bankalar gerçek görevler üzerinden sürekli dijital güvenlik eğitimi sağlayabilir. Düzenleyiciler yüksek riskli kategorilerde reklam arşivi, satıcı izlenebilirliği, gecikmeli transfer ve kolay bildirim mekanizmalarını zorunlu kılabilir. Mağduriyet bildiriminde utanç ve öz suçlama azaltılmalı; bildirim süreci cezalandırıcı değil, telafi ve öğrenme odaklı tasarlanmalıdır (Parti vd., 2025).

5.6 Sınırlılıklar ve sonuç

Bu çalışma kavramsal bir sentezdir ve önerilen nedensel yolları doğrudan test etmemektedir. Kullanılan bulguların önemli bölümü kesitsel, öz bildirime dayalı ve sağlık teknolojileri bağlamındadır. Sağlık, ödeme ve genel sosyal ticaretin risk yapıları farklı olduğundan katsayıların bağlamlar arasında taşınması uygun değildir. 2025 ve 2026 tarihli çalışmaların bir kısmı belirli ülke ve örneklemlere dayanır; kültürel, düzenleyici ve altyapısal farklılıklar ilişkilerin yönünü ve gücünü değiştirebilir. Ayrıca bilişsel kapasiteye ilişkin grup ortalamaları bireysel yetersizlik tanısı olarak yorumlanmamalıdır.

Buna rağmen literatürün ortak yönü açıktır: ileri yaş tüketicilerin sosyal ticarete katılımı algılanan fayda ve kolaylıktan fazlasına bağlıdır. Bilgi asimetrisi, bilişsel yük ve platform opaklığı riski yükseltirken; doğrulanabilir sinyaller, prosedürel şeffaflık, görev özgü öz yeterlik ve destekleyici sosyal çevre güvenin niteliğini belirler. Dijital bağımsızlık, daha fazla kullanımın otomatik sonucu değildir. Tüketicinin seçimi anlayabilmesi, gerektiğinde durabilmesi, hatayı geri alabilmesi ve yardım üzerinde kontrol sahibi

olması gerekir. Bu yaklaşım, gümüş ekonomide büyüme hedefini tüketici özerkliği ve hakkaniyetle aynı analitik çerçevede buluşturur.

Çalışmanın ulaştığı temel sonuç, sosyal ticarete katılımın yalnızca algılanan fayda, kullanım kolaylığı veya teknolojiye erişimle açıklanamayacağıdır. İleri yaş tüketicinin bir platformu kullanması, karar sürecini anladığı, karşılaştığı riskleri doğru değerlendirdiği veya işlemi kendi hedefleri doğrultusunda yönetebildiği anlamına gelmez. Bu nedenle model, kullanım ve satın alma niyetini nihai başarı ölçütü olmaktan çıkararak dijital bağımsızlığa giden ara sonuçlar olarak konumlandırmaktadır. Esas başarı, tüketicinin seçenekleri karşılaştırabilmesi, güvenilirlik sinyallerini doğrulayabilmesi, belirsizlik yükseldiğinde durabilmesi, hatalı işlemi geri alabilmesi ve ihtiyaç duyduğu yardımı hesap kontrolünü kaybetmeden kullanabilmesidir.

Bu çerçevede güvenin yüksekliği kadar doğruluğu da önem taşımaktadır. Eksik güven, yararlı dijital hizmetlerden uzaklaşmaya ve ekonomik ya da toplumsal fırsatların kaçırılmasına yol açabilirken, aşırı güven dolandırıcılık, mahremiyet kaybı ve telafisi güç işlemler karşısında kırılganlığı artırabilir. Kalibre edilmiş güven, platformun gerçek güvenilirliği ile tüketicinin güven düzeyi arasındaki uyumu ifade eder. Bu uyum; satıcı kimliğinin doğrulanabilirliği, sponsorlu içeriğin açıklığı, toplam fiyatın zamanında gösterilmesi, veri kullanımının anlaşılır biçimde sunulması ve uyuşmazlık durumunda sorumlu aktör ile başvuru yolunun görünür olması sayesinde güçlenir. Kolayca taklit edilebilen rozetler veya uzun hukuki açıklamalar ise güven görüntüsü üretse de karar kalitesini aynı ölçüde artırmayabilir.

Bilgi asimetrisi, bilişsel yük ve platform opaklığı birlikte değerlendirildiğinde dijital kırılganlığın bireysel bir yetersizlik olmadığı daha açık biçimde görülmektedir. Arayüz karmaşıklığı, çok sayıda seçenek, belirsiz simgeler, yanıltıcı tasarım örüntüleri ve algoritmik sıralamanın görünmezliği, tüketicinin sınırlı dikkat ve çalışma belleği kaynaklarını ürün değerlendirmesinden sistem çözümlemeye aktarır. Böyle bir ortamda tanıdık logoya, sosyal kanıta veya varsayılan seçeneğe yönelmek irrasyonel bir davranıştan çok yüksek işlem maliyetine verilen bir yanıt olabilir. Dolayısıyla riskin azaltılması, kullanıcının daha dikkatli olmasını istemekle sınırlanamaz; platformun karar yükünü azaltması, kritik bilgiyi doğru anda sunması ve işlemleri geri döndürülebilir kılması gerekir.

İleri yaş tüketicilerin kendi içindeki farklılıklar da modelin önemli bir sonucudur. Kronolojik yaş; eğitim, gelir, sağlık, önceki teknoloji deneyimi, yaşam düzeni ve sosyal destekle birlikte işleyen genel bir göstergedir. Bu nedenle ileri yaş grubunu yeniliğe kapalı, teknoloji karşısında çaresiz veya aynı düzeyde korunmaya muhtaç tek bir segment olarak ele almak hem analitik olarak yanıltıcı hem de dijital yaş ayrımcılığını güçlendirici olabilir. Kapasite uyumu yaklaşımı, seçenekleri kullanıcı adına azaltmak yerine sistemin talep ettiği bilişsel ve sosyal kaynaklarla kullanıcının mevcut kaynakları arasındaki dengeyi kurmayı öne çıkarır. Katmanlı bilgi, düz gezinme, okunabilir tipografi, kalıcı karşılaştırma ve açık geri bildirim bu dengeyi destekleyen temel unsurlardır.

Sosyal desteğin rolü de yalnızca olumlu veya olumsuz olarak sınıflandırılamaz. Aile ve akran desteği riskli işlemin fark edilmesini, bilgi kaynağının doğrulanmasını ve kaybın büyümeden önlenmesini sağlayabilir. Bununla birlikte yardımın sürekli olarak görevi kullanıcı adına tamamlaması, parola ve hesap kontrolünün devredilmesi ya da kararın bütünüyle başkası tarafından verilmesi dijital bağımsızlığı zayıflatır. Destekleyici uygulama, işlemi devralmak yerine beceri ve kontrol aktarımı yaratmalıdır. Paylaşılabilir işlem önizlemesi, sınırlı yetkili yardımcı hesabı, kullanıcı tarafından geri alınabilen onay ve erişilebilir insan desteği, koruma ile özerklik arasındaki bu hassas dengeyi kurumsal tasarım içinde görünür hâle getirebilir.

Platform yöneticileri açısından sonuç, güveni yalnızca dönüşüm oranı veya kullanım süresi üzerinden ölçmemenin gerekliliğidir. Yanlış satın alma, işlemden vazgeçme, iptal başarısı, şikâyetin çözülme süresi, yüksek riskli işlemlerde doğrulama davranışı ve güvenli yardım kullanımı da değerlendirmeye alınmalıdır. Yaş dostu deneyim, ileri yaş kullanıcılar için ayrı ve küçültülmüş bir arayüz üretmekten çok evrensel tasarım ilkelerini bütün platforma yerleştirmeyi gerektirir. Satıcı izlenebilirliği, açık reklam etiketi, güvenli varsayılanlar, anlaşılır kimlik doğrulama, toplam fiyatın erken görünmesi ve etkili telafi süreçleri yalnızca ileri yaş grubunun değil, tüm kullanıcıların karar güvenliğini güçlendiren yapısal güvencelerdir.

Kamusal politika bakımından bireysel eğitim ile yapısal koruma birbirinin yerine geçen araçlar değildir. Görev temelli ve sürekli dijital güvenlik eğitimi, kaynak değerlendirme, ticari niyeti tanıma, veri izini kavrama ve telafi yollarını kullanma kapasitesini geliştirebilir. Ancak eğitim, platformların daha iyi bilgiye ve davranışsal öngörüye sahip olmasından doğan sorumluluğu ortadan kaldırmaz. Yüksek riskli kategorilerde satıcı kimliğinin doğrulanması, reklam ve sponsorluk kayıtlarının izlenebilirliği, şüpheli

transferlerde geri dönüş süresi ve kolay mağduriyet bildirimi gibi önlemler riskin kurumsal olarak paylaşılmasını sağlar. Bildirim süreçlerinin utanç ve öz suçlamayı artırmaması, telafi ile öğrenmeyi birlikte desteklemesi özellikle önemlidir.

Önerilen ilişkilerin sınanması için gelecekteki araştırmaların öz bildirime dayalı kesitsel niyet ölçümlerinin ötesine geçmesi gerekir. Sinyal kalitesi ile arayüz yükünü bağımsız olarak değiştiren deneyler, yüksek güven ile doğru güveni birbirinden ayırabilir. Boylamsal çalışmalar, eğitim ve desteğin etkisinin sürüp sürmediğini; görev temelli gözlemler ise kullanıcının hangi noktada yardım istediğini, işlemi bıraktığını veya hatayı geri aldığını gösterebilir. Dijital bağımsızlık ölçümü görev tamamlama, bilgi doğrulama, gizlilik tercihi, hata telafisi, yardımın kontrolü ve algoritmik özerklik boyutlarını birlikte içermelidir. Yaş alt grupları, ürün kategorileri, kültürel bağlam ve aile desteği bu ilişkilerin yönünü ve gücünü değiştirebilecek koşullar olarak ayrıca ele alınmalıdır.

Sonuç olarak gümüş ekonominin dijital büyümesi, ileri yaş tüketicilerin platformlarda daha fazla bulunmasıyla değil, bu katılımın ne ölçüde güvenli, anlaşılır ve denetlenebilir olduğuyla değerlendirilmelidir. Sosyal ticaret ekonomik erişim, sosyal bağ ve gündelik kolaylık yaratırken aynı zamanda bilgi asimetrisini, bilişsel yükü ve veri temelli yönlendirmeyi yoğunlaştırabilir. Kalibre edilmiş güven bu gerilimi yönetmenin, dijital bağımsızlık ise sonuçlarını değerlendirmenin temel kavramlarıdır. Tüketici seçimini anlayabiliyor, güvenilirliği sınayabiliyor, gerektiğinde durabiliyor, işlemi geri alabiliyor ve yardım üzerinde kontrolünü koruyabiliyorsa dijital katılım güçlendirici bir niteliğe kavuşur. Böylece ekonomik büyüme, tüketici özerkliği ve hakkaniyet aynı değerlendirme çerçevesinde buluşabilir.

Kaynakça

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TÜRKİYE'DE İLLER DÜZEYİNDE TARIMSAL ÜRETİM ETKİNLİĞİ

AGRICULTURAL PRODUCTION EFFICIENCY BY PROVINCE IN TURKEY

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ÖZET
Bu çalışmanın temel amacı, Türkiye'de iller düzeyinde tarımsal üretim etkinliğini çıktı yönelimli bir yaklaşım çerçevesinde ölçmek ve değerlendirmektir. Araştırmada karar verme birimleri olarak Türkiye'nin tarım sektöründe önemli 20 ili ele alınmıştır. Analizlerde girdi değişkenleri olarak işlenen tarım alanı (dekar) ve tarımsal mekanizasyon (traktör ve tarım alet-ekipman sayısı); çıktı değişkenleri olarak ise sebze-meyve üretimi (ton) ve tahıl ve diğer bitkisel üretim (ton) kullanılmıştır. Yöntem olarak parametrik olmayan sınır yaklaşımlarından Veri Zarflama Analizi (VZA) tercih edilmiş olup, çıktı yönelimli Charnes-Cooper-Rhodes (CCR) ve Banker-Charnes-Cooper (BCC) modelleri uygulanmıştır. Çalışmada literatürde yer alan Türkiye tarım sektörü etkinlik çalışmaları ve il düzeyindeki bitkisel üretim verileri kapsamlı bir şekilde incelenmiştir. Araştırma bulguları, illerin mevcut girdi düzeylerini sabit tutarak çıktılarını ne ölçüde artırabileceğini ortaya koymaktadır. Bu doğrultuda, illerin göreli etkinlik skorları hesaplanmış, etkin olmayan iller için potansiyel çıktı artış oranları belirlenmiş ve tarımsal etkinsizliğin kaynakları analiz edilmiştir. Elde edilen bulgular, Türkiye'de bölgesel tarım politikalarının planlanması, mekanizasyonun etkin kullanımı ve tarımsal arazilerin sürdürülebilir yönetimi açısından önemli çıkarımlar sunmaktadır.Bu çalışma, Türkiye'de tarımsal üretimin iller düzeyindeki etkinliğini çıktı yönelimli bir çerçevede ölçmeyi amaçlamaktadır. İnceleme, bitkisel üretim açısından öne çıkan 20 ilin 2025 yılına ait verilerine dayanmaktadır. Karar verme birimi olarak ele alınan iller için girdi değişkenleri işlenen tarım alanı (dekar) ile tarımsal mekanizasyon düzeyi (traktör ile tarım alet-ekipman sayısı); çıktı değişkenleri ise sebze-meyve üretimi ile tahıl ve diğer bitkisel ürünlerin üretim miktarıdır (ton). Etkinlik ölçümünde parametrik olmayan sınır yöntemlerinden Veri Zarflama Analizi (VZA) kullanılmış; ölçeğe göre sabit getiri varsayan Charnes-Cooper-Rhodes (CCR) ile değişken getiriyi esas alan Banker-Charnes-Cooper (BCC) modelleri çıktı yönelimli biçimde çözülmüştür. İki modelin birlikte değerlendirilmesiyle illerin toplam teknik, saf teknik ve ölçek etkinlikleri ayrıştırılmış; etkinsiz iller için mevcut girdilerle erişilebilecek potansiyel çıktı artışları ve etkinsizliğin kaynakları belirlenmiştir. Elde edilen sonuçlara göre 20 ilin ortalama toplam teknik etkinlik skoru 0,74 düzeyinde olup altı il her iki modelde de tam etkindir; etkinsiz illerde sorun ağırlıklı olarak teknik aksaklıklardan çok uygun olmayan işletme ölçeğinden kaynaklanmaktadır. Bu bulgular; tarımsal desteklerin bölgesel etkinlik ve getiri yapısına göre farklılaştırılması, mekanizasyon kapasitesinin atıl bırakılmadan kullanılması ve tarım arazilerinin sürdürülebilir yönetimi açısından politika çıkarımları içermektedir.
Anahtar Kelimeler: Tarımsal Etkinlik, Veri Zarflama Analizi, Çıktı Yönelimli CCR, Çıktı Yönelimli BCC, Türkiye.

ABSTRACT
The primary objective of this study is to measure and evaluate the efficiency of agricultural production at the provincial level in Turkey within the framework of an output-oriented approach. The study focuses on 20 provinces that play a significant role in Turkey's agricultural sector as decision-making units. The analyses used agricultural land area (dekar) and agricultural mechanization (number of tractors and agricultural tools and equipment) as input variables, and vegetable and fruit production (metric tons) and grain and other crop production (metric tons) as output variables. Data Envelopment Analysis (DEA), a non-parametric frontier approach, was selected as the method, and the output-oriented Charnes-Cooper-Rhodes (CCR) and Banker-Charnes-Cooper (BCC) models were applied. The study comprehensively reviewed existing literature on efficiency studies in Turkey's agricultural sector and provincial-level crop production data. The research findings reveal the extent to which provinces can

increase their output while keeping current input levels constant. Accordingly, the provinces' relative efficiency scores were calculated, potential output growth rates were determined for inefficient provinces, and the sources of agricultural inefficiency were analyzed. The findings provide important insights for the planning of regional agricultural policies in Turkey, the effective use of mechanization, and the sustainable management of agricultural lands.This study measures the efficiency of agricultural production across Turkish provinces within an output-oriented framework. The analysis draws on 2025 data for twenty provinces that stand out in crop production. Treating each province as a decision-making unit, cultivated agricultural land (in decares) and agricultural mechanization (the number of tractors and agricultural tools and equipment) are used as inputs, while vegetable and fruit output together with the output of cereals and other crops (both in tons) are used as outputs. Efficiency is estimated through Data Envelopment Analysis (DEA), a non-parametric frontier method; the Charnes-Cooper-Rhodes (CCR) model under constant returns to scale and the Banker-Charnes-Cooper (BCC) model under variable returns to scale are solved in their output-oriented forms. By combining the two models, the total technical, pure technical and scale efficiencies of the provinces are decomposed, and for the inefficient provinces the potential output gains attainable with existing inputs and the sources of inefficiency are identified. The results show that the average total technical efficiency score is about 0.74 and that six provinces are fully efficient under both models; in the inefficient provinces, the problem stems mainly from a suboptimal operating scale rather than from managerial shortcomings. These findings offer policy implications for differentiating agricultural support according to regional efficiency and returns structures, for keeping mechanization capacity from remaining idle, and for the sustainable management of farmland.

Keywords: Agricultural Efficiency, Data Envelopment Analysis, Output-Oriented CCR, Output-Oriented BCC, Turkey.

1. GİRİŞ

Tarım sektörü; beslenmenin temelini oluşturan gıda maddelerini üretmesi, sanayiye hammadde sağlaması, kırsal nüfusa istihdam yaratması ve dış ticarete katkısı nedeniyle bütün ekonomilerde olduğu gibi Türkiye'de de stratejik bir konuma sahiptir. Hızlı nüfus artışı, iklim değişikliği ve küresel rekabetin getirdiği baskılar, sınırlı olan tarımsal kaynakların verimli ve etkin kullanımını giderek daha öncelikli bir mesele hâline getirmektedir. Özellikle gelişmekte olan ekonomilerde kalkınmanın itici güçlerinden biri sayılan tarım, sürdürülebilirliği koruyarak birim alandan alınan üretimi artırabilmek için kaynak kullanım performansını en üst düzeye çıkarmak durumundadır (Bölük, 2015).

Türkiye, coğrafi konumu, iklim çeşitliliği ve geniş ekilebilir alanlarıyla yüksek bir bitkisel üretim potansiyeli barındırmaktadır. Ne var ki arazilerin miras yoluyla sürekli bölünmesinden doğan parçalı mülkiyet yapısı, mekanizasyonun düzensiz ve yetersiz kullanımı ile modern girdilere erişimdeki bölgesel dengesizlikler bu potansiyelin tam olarak değerlendirilmesini engellemektedir (Erdoğan Aktan & Kaya Samut, 2013). Söz konusu yapısal kısıtlar, üretim artışının yeni kaynak aktarımından çok eldeki kaynakların ne ölçüde etkin kullanıldığıyla ilgili bir sorun olduğunu göstermekte; böylelikle verimlilik ve etkinlik kavramlarını tarım politikası tartışmalarının merkezine taşımaktadır.

İktisat yazınında verimlilik (productivity), kullanılan girdiler ile elde edilen çıktılar arasındaki fiziksel oranı ifade ederken; etkinlik (efficiency), bir karar biriminin mevcut üretim teknolojisinin tanımladığı en iyi uygulama sınırında faaliyet gösterip göstermediğini değerlendirir (Aydın & Borat, 2021). Üretken etkinliğin bir sınır kavramı çerçevesinde ölçülebileceği düşüncesi literatüre ilk olarak Farrell tarafından kazandırılmış (Farrell, 1957); bu yaklaşım daha sonra, çoklu girdi ve çıktıyı önsel bir fonksiyonel biçim varsaymaksızın değerlendirebilen ve doğrusal programlamaya dayanan Veri Zarflama Analizi'nin (VZA) gelişimine zemin hazırlamıştır (Charnes, Cooper & Rhodes, 1978). Böylece tarımsal performansın iyileştirilmesi, girdilerin kısılmasından çok mevcut kaynak sınırları içinde üretimin azamileştirilmesine bağlı bir mesele olarak ele alınmaya başlanmıştır.

Türkiye tarımında etkinlik ölçümüne yönelik çalışmalar incelendiğinde, bunların büyük ölçüde belirli bölgeler ya da tek tek ürün grupları düzeyinde yoğunlaştığı görülmektedir (Bayav & Karlı, 2020). Bu çalışma ise analizi ülke geneline ve il düzeyine taşıyarak, bitkisel üretimin en temel iki girdisi olan işlenen tarım alanı ile tarımsal mekanizasyonu; üretimin iki ana çıktı grubu olan sebze-meyve üretimi ve tahıl ile diğer bitkisel ürünlerin üretimiyle ilişkilendirmektedir. İl düzeyinde ve iki girdi-iki çıktı yapısıyla kurulan bu çerçeve, bölgesel kaynak tahsisine ilişkin karşılaştırmalı bir değerlendirme imkânı sunması bakımından mevcut yazına katkı sağlamayı hedeflemektedir.

Yöntem olarak çıktı yönelimli CCR ve BCC modellerinin seçilmesi rastlantısal bir tercih olmayıp ülkenin tarım politikasının önceliğiyle örtüşmektedir; zira tarım toprakları ve makine parkı gibi girdilerin kısa dönemde azaltılması ne uygulanabilir ne de gıda arz güvenliği bakımından arzu edilir bir seçenektir. Bu nedenle asıl hedef, mevcut girdi düzeyini koruyarak üretimi artırmaktır. Bu doğrultuda çalışma; illerin tarımsal üretim etkinliklerini göreli olarak belirlemeyi, etkinsiz illerde mevcut girdilerle erişilebilecek potansiyel çıktı artışlarını hesaplamayı, etkinsizliğin kaynaklarını saf teknik ve ölçek bileşenlerine ayrıştırmayı ve elde edilen bulgular ışığında bölgesel düzeyde farklılaştırılmış politika önerileri geliştirmeyi amaçlamaktadır.

2. TÜRKİYE'DE TARIMSAL ÜRETİM YAPISI VE GİRDİLER

Türkiye tarımı, ekonomik dönüşüm sürecinde payı görece azalsa da üretim, istihdam ve gıda arzı bakımından stratejik konumunu korumaktadır. Bu yapının en belirgin özelliği, üretim teknolojisinin ve kaynak donanımının iller arasında türdeş olmamasıdır; toprak verimliliği, sulama imkânları, işletme ölçeği ve sermaye yoğunluğu bakımından belirgin bir bölgesel ikilik gözlenmektedir. Söz konusu farklılaşma, tarımsal performansın ulusal ortalamalar üzerinden değil, karar birimi olarak iller düzeyinde değerlendirilmesini gerektirir. Bir ilin etkinliği, sahip olduğu girdileri en iyi uygulama sınırına ne ölçüde yaklaştırarak çıktıya dönüştürdüğüyle ölçüldüğünden, girdi yapısının ve üretim bileşiminin ayrıntılı biçimde ele alınması gerekmektedir.

Bitkisel üretimin temel ve kısa dönemde ikame edilemeyen girdisi işlenen tarım alanıdır. Türkiye'de bu alanların toplam büyüklüğü; kentleşme, sanayi amaçlı arazi kullanımı ve bir bölümünün atıl ya da nadas konumuna geçmesi nedeniyle son yıllarda genişlemekten çok durağanlaşmış, kimi bölgelerde gerilemiştir. Ancak asıl yapısal sorun, alanın mutlak büyüklüğünden çok parçalı mülkiyet yapısıdır; miras yoluyla sürekli bölünen ve ortalama işletme büyüklüğü düşük kalan araziler makine kullanımını, sulama yatırımını ve ölçek ekonomilerinden yararlanmayı sınırlandırmaktadır (Erdoğan Aktan & Kaya Samut, 2013). Toprak arzının kısa dönemde esnek olmaması, üretim artışının yeni alan açmaktan çok birim alandan alınan verimin, yani teknik etkinliğin yükseltilmesine bağlı olduğunu göstermekte; bu durum çalışmada çıktı yönelimli bir yaklaşımın benimsenmesini de gerekçelendirmektedir.

Tarımsal mekanizasyon, işgücünü ikame ederek emek verimliliğini artıran, zamana duyarlı işlemleri hızlandıran ve hasat kayıplarını azaltan başlıca sermaye girdisidir. Mekanizasyonun yaygın göstergesi olan traktör ve buna bağlı alet-ekipman parkı ülke genelinde dengesiz dağılmıştır; arazi yapısının elverişli olduğu ve ticari tarımın gelişkin olduğu Marmara, Ege ve İç Anadolu'da makine yoğunluğu yüksekken, engebeli topografyaya sahip Doğu Karadeniz ve Doğu Anadolu'da kullanım görece sınırlı kalmaktadır (Karaman & Özalp, 2017). Bununla birlikte mekanizasyonda belirleyici olan yalnızca makine varlığı değil, mevcut kapasitenin ne ölçüde kullanıldığıdır; ölçeğe uygun olmayan ya da atıl bir makine parkı, girdi fazlalığı yaratarak illeri etkinlik sınırından uzaklaştırmaktadır. Bu nedenle mekanizasyon düzeyi ve kapasite kullanımı, iller bazında hesaplanan etkinlik skorlarını doğrudan biçimlendiren bir etkendir.

Türkiye'de bitkisel üretim, nitelikleri ve üretim koşulları belirgin biçimde ayrışan iki ana grupta toplanabilir. Tahıllar ve diğer bitkisel ürünler (buğday, arpa, mısır, baklagiller ve endüstri bitkileri) genellikle geniş ve kuru tarım alanlarında üretilen, gıda güvenliğinin temelini oluşturan ürünlerdir. Sebze ve meyve üretimi ise katma değeri yüksek, sulama ve gübre kullanımı yoğun, birim alandan daha fazla gelir getiren ve önemli bir bölümü ihracata yönelen faaliyetleri kapsar (Aydın & Borat, 2021). Bu iki grubun coğrafi dağılımı, illerin iklim, toprak ve sulama koşullarına göre belirgin biçimde farklılaşmakta; benzer girdi donanımına sahip iller dahi ürün bileşimlerine bağlı olarak farklı çıktı düzeylerine ulaşabilmektedir. Dolayısıyla illerin işlenen alan ve mekanizasyon girdileriyle her iki çıktı grubunda sağladıkları etkinliğin birlikte ölçülmesi, bölgesel kaynak tahsisinin ve tarım politikalarının daha sağlıklı tasarlanması bakımından belirleyici bir öneme sahiptir.

3. LİTERATÜR İNCELEMESİ

Tablo 1: Türkiye Tarım Sektöründe Yapılan Etkinlik ve Verimlilik Çalışmaları Literatür Tablosu

Yazarlar ve Yıl	Çalışmanın Amacı	Veri Seti / Örneklem	Yöntem	Girdi Değişkenleri	Çıktı Değişkenleri	Temel Bulgular ve Sonuçlar
Çakmak ve Zaim (1992)	Türkiye tarım kesiminde teknik etkinlik, ölçek ve girdi kalabalıklaşması bileşenlerini boylamsal olarak incelemek.	1967-1987 yılları arası Türkiye tarım sektörü zaman serisi verileri.	Deterministik parametrik olmayan üretim sınırı yaklaşımı (VZA tabanlı ayrıştırma).	Tarımsal alan, suni gübre, tarımsal işgücü, traktör sayısı.	Reel tarımsal üretim değeri.	Tarım kesimi 1981'e kadar teknik etkinlik açısından olumlu seyretmiş, sonrasında etkinsizlik artmıştır. Etkinsizliğin en önemli kaynağı girdi kalabalıklaşmasıdır.
Öcal, Çakmak ve Dudu (2007)	TÜBİTAK Projesi (SOBAG-105K030) kapsamında hanehalkı düzeyinde tarımsal verimlilik ve etkinsizlik kaynaklarını incelemek.	2002 ve 2004 yılları, Türkiye genelinde 3000'den fazla hanehalkı panel verisi.	Stokastik Sınır Analizi (SSA).	Toprak, işgücü, makine, diğer girdiler.	Tarımsal üretim değeri.	Batı bölgeleri daha verimlidir. Tarımda işgücü fazlası vardır. Sulama, eğitim düzeyi ve çiftlik büyüklüğü verimliliği artıran ana faktörlerdir.
Çakmak, Dudu ve Öcal (2008)	Türk tarım sektöründeki teknik etkinlik ve verimliliği mikroekonomik düzeyde analiz etmek.	2002 ve 2004 yılları, Türkiye genelinde 3000'den fazla çiftçi hanehalkı anket verisi.	Stokastik Sınır Analizi (SSA) (ZİDE, TEE ve YTEE modelleri).	Toprak, işgücü, sermaye (traktör/makine), ara girdiler (gübre, tohum, ilaç, sulama vb.).	Tarımsal hasılat / üretim değeri.	Ortalama teknik etkinlik 2002'de %33, 2004'te %45'tir. Arazi kiralama durumu ve arazi parçalılığı etkinliği olumsuz etkilemektedir.
Erdoğan Aktan ve Kaya Samut (2013)	Türk tarımının etkinlik bileşenlerini ve bu etkinliği etkileyen sosyo-ekonomik faktörleri iki aşamalı olarak analiz etmek.	2000-2009 yılları arası, Türkiye'nin 81 ili.	İki aşamalı VZA ve Tobit Regresyonu.	İşlenen tarım alanı, traktör sayısı, kimyasal gübre, işgücü.	Toplam tarımsal üretim değeri.	İllerin tarımsal etkinlikleri zamana göre dalgalanmaktadır. Arazi parçalılığı ve düşük eğitim etkinsizliği artıran temel faktörlerdir.
Bölük (2015)	Gelişmekte olan ve hızlı büyüyen BRICS ve MINT ülkelerinin tarım sektörlerini karşılaştırmalı olarak analiz etmek.	2010-2013 dönemi, BRICS ve MINT ülkeleri.	Malmquist Toplam Faktör Verimliliği (MTFV) endeksi.	Tarım alanı, traktör sayısı, gübre, işgücü.	Tarımsal üretim değeri.	Türkiye'nin tarımsal verimlilik artış hızı ve teknolojik gelişim dinamikleri diğer ülkelerle karşılaştırmalı olarak tartışılmıştır.
Karaman ve Özalp (2017)	Türkiye tarım sektörünün bölgesel toplam faktör verimliliğini belirlemek.	NUTS-1 düzeyindeki 12 bölge.	Malmquist Verimlilik Endeksi.	Tarım alanı, traktör sayısı, gübre tüketimi, işgücü.	Bölgesel tarımsal üretim değeri.	Ulusal düzeyde verimlilikte yıllık %1 büyüme saptanmış olup, bu büyümenin esas kaynağının teknik etkinlik artışı

						olduğu rapor edilmiştir.
Bayav ve Karlı (2020)	Türkiye'de tarım sektöründe yapılmış etkinlik çalışmalarını bibliyometrik olarak incelemek.	1994-2016 yılları arasında yayınlanmış 138 adet etkinlik çalışması.	Bibliyometrik Analiz.	- (Bibliyometrik çalışma)	- (Bibliyometrik çalışma)	Çalışmaların %67.4'ünde VZA, %15.9'unda Stokastik Sınır Analizi (SSA) kullanıldığı belirlenmiştir.
Menten, Çekiç ve Atıcı (2020)	Türkiye tarım sektöründe ürün bazında makro ölçekli bir etkinlik ve verimlilik değerlendirmesi yapmak.	2010-2016 dönemi, üretimi yapılan 61 bitkisel ürün.	VZA ve Malmquist Toplam Faktör Verimliliği (MTFV) endeksi.	Tarım alanı, tohum, gübre, ilaç, mazot, işgücü.	Ürün bazında üretim miktarları (ton).	En yüksek sayıda etkin birime sebzelerde ulaşılmıştır. Tarımsal verimlilikteki gerilemenin temel nedeni teknolojik gerilemedir.
Aydın ve Borat (2021)	Bitkisel üretim değeri en yüksek olan 20 ilin tarımsal etkinliklerini çıktı yönelimli olarak ölçmek.	2019 yılı, bitkisel üretim değeri en yüksek 20 il.	Çıktı yönelimli CCR ve BCC Veri Zarflama Analizi (VZA).	İşlenen tarım alanı, tarımsal mekanizasyon, sulamada kullanılan enerji, gübre tüketimi.	Sebze-meyve üretimi (ton), tahıl ve diğer bitkisel üretim miktarları (ton).	Çıktı yönelimli CCR modeline göre 11 il, BCC modeline göre ise 10 il göreli olarak etkin saptanmıştır.

4. YÖNTEM

Veri Zarflama Analizi (VZA), benzer girdileri kullanarak benzer çıktılar üreten karar verme birimlerinin (KVB) göreli etkinliklerini ölçmeye yarayan, doğrusal programlamaya dayalı ve parametrik olmayan bir sınır analizi yöntemidir. Yöntemin kavramsal temeli *Farrell (1957)* tarafından atılmış; çok girdili ve çok çıktılı duruma genişletilerek doğrusal programlama biçiminde ilk kez *Charnes, Cooper ve Rhodes (1978)* tarafından formüle edilmiştir. VZA, gözlenen en iyi performanslı birimleri birleştirerek ampirik bir üretim (etkinlik) sınırı oluşturur ve her birimin etkinliğini bu sınıra olan uzaklığıyla ölçer; yöntemin adındaki 'zarflama' ifadesi, tüm gözlemleri çevreleyen bu sınırın oluşturulmasına atıfta bulunur. Girdiler ile çıktılar arasında önsel bir fonksiyonel ilişki varsaymaması ve fiyat bilgisine gerek duymadan birden çok girdi ile çıktıyı eşzamanlı değerlendirebilmesi, yöntemi tarımsal etkinlik çalışmaları için elverişli kılmaktadır (*Aydın & Borat, 2021*).

VZA modelleri, amaç fonksiyonunun yönelimine göre girdi ya da çıktı yönelimli olarak kurulabilir. Girdi yönelimli modellerde belirli bir çıktı düzeyi en az girdiyle üretilmeye çalışılırken; çıktı yönelimli modellerde girdi düzeyi sabit tutularak çıktının olabildiğince artırılması amaçlanır (*Menten, Çekiç & Atıcı, 2020*). Türkiye'de tarım arazileri ve traktör parkı gibi girdilerin kısa dönemde azaltılması ne uygulanabilir ne de gıda arz güvenliği açısından arzu edilir olduğundan, üretimin artırılması temel politika hedefini oluşturmaktadır. Bu nedenle çalışmada çıktı yönelimli modeller tercih edilmiş; analiz, ölçeğe göre sabit getiri varsayan CCR ile değişken getiriyi esas alan BCC modellerinin birlikte çözülmesi üzerine kurulmuştur (*Banker, Charnes & Cooper, 1984*).

İki modelin birlikte kullanılması, toplam teknik etkinliğin saf teknik etkinlik ve ölçek etkinliği bileşenlerine ayrıştırılmasına imkân vererek etkinsizliğin yönetsel mi yoksa ölçeksel mi olduğunun belirlenmesini sağlamaktadır. Etkinsiz bulunan her birim için yöntem, kendisine en yakın etkin birimlerden oluşan bir referans kümesi tanımlar; bu küme, ilgili birimin ulaşması gereken hedef değerleri ortaya koymaktadır (*Cooper, Seiford & Tone, 2006*). Ayrıca VZA'nın deterministik bir yöntem olduğu ve sınırdan sapmaların tümünü etkinsizlik olarak yorumladığı; dolayısıyla ölçüm hatalarına ve uç gözlemlere duyarlı olabileceği göz önünde bulundurulmalıdır. Aşağıda, çalışmada uygulanan çıktı yönelimli CCR ve BCC modellerinin matematiksel formülasyonları sırasıyla açıklanmıştır.

4.1. Çıktı Yönelimli CCR Modeli

Charnes, Cooper ve Rhodes (1978) tarafından geliştirilen CCR modeli, Ölçeğe Göre Sabit Getiri (Constant Returns to Scale - CRS) varsayımı altında çalışır. Bu model, girdilerdeki oransal bir artışın çıktılarda da aynı oranda artışa neden olacağını varsayar. Gözlenen n adet karar verme birimi (il) olduğu, her bir j ($j = 1, \dots, n$) biriminin m adet girdi kullanarak s adet çıktı ürettiği varsayımı altında, etkinlik skoru hesaplanan k. karar birimi için çıktı yönelimli dual doğrusal programlama formülasyonu aşağıdaki gibidir (Cooper, Seiford & Tone, 2006):

$\max_{\phi,\lambda} \phi$ **(1)**

$s.t.\ \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{ik},\ i = 1, \dots, m$ **(2)**

$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \phi y_{rk},\ r = 1, \dots, s$ **(3)**

$\lambda_j \geq 0,\ j = 1, \dots, n$ **(4)**

Burada, ϕ ($1 \leq \phi < \infty$) analizi yapılan k. ilin çıktı yönelimli etkinlik skorunu gösteren serbest değişkendir. Eğer $\phi = 1$ ise, ilgili il etkinlik sınırı üzerindedir ve göreli olarak tam etkindir. $\phi > 1$ ise, il teknik olarak etkinsizdir ve çıktısını mevcut girdileriyle $(\phi - 1) \times 100$ oranında artırma potansiyeline sahiptir. λ_j ($j = 1, \dots, n$), etkinsiz illerin referans kümelerindeki ağırlıklarını gösteren katsayılar vektörüdür. x_{ij} ve y_{rj} sırasıyla j. ilin kullandığı i. girdi miktarını (işlenen alan, mekanizasyon) ve ürettiği r. çıktı miktarını (sebze-meyve, tahıl ve bitkisel üretim) temsil etmektedir. x_{ik} ve y_{rk} ise analizi yapılan k. ilin mevcut girdi ve çıktı miktarlarıdır. Tablo 4 ve devamında raporlanan etkinlik skorları, yorumlama kolaylığı açısından ϕ değerinin tersi ($1/\phi$) alınarak [0,1] aralığına ölçeklenmiş değerlerdir; bu ölçekte skoru 1,0000 olan iller tam etkin kabul edilmekte, etkinsiz bir ilin potansiyel çıktı artışı ise (1/skor - 1) × 100 ifadesiyle hesaplanmıştır.

4.2. Çıktı Yönelimli BCC Modeli

Banker, Charnes ve Cooper (1984) tarafından geliştirilen BCC modeli, ölçeğe göre sabit getiri varsayımını esneterek Ölçeğe Göre Değişken Getiri (Variable Returns to Scale - VRS) varsayımını kabul eder. Bu model, tarımsal üretimde ölçeğin büyüklüğüne bağlı olarak artan, azalan veya sabit getiri durumlarının geçerli olabileceğini öngörür. BCC modeli, CCR modelinin kısıtlar kümesine konveksite kısıtı olarak adlandırılan $\sum \lambda_j = 1$ kısıtının eklenmesiyle elde edilir ve illerin "saf teknik etkinlik" değerini ölçer. Çıktı yönelimli dual BCC doğrusal programlama modeli şu şekildedir:

$\max_{\phi,\lambda} \phi$ **(5)**

$s.t.\ \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_{ik},\ i = 1, \dots, m$ **(6)**

$\sum_{j=1}^{n} \lambda_j y_{rj} \geq \phi y_{rk},\ r = 1, \dots, s$ **(7)**

$\sum_{j=1}^{n} \lambda_j = 1$ **(8)**

$\lambda_j \geq 0,\ j = 1, \dots, n$ **(9)**

Modelde yer alan $\sum_{j=1}^{n} \lambda_j = 1$ konveksite kısıtı, analiz edilen ilin sadece kendi ölçeğine yakın büyüklükteki etkin illerden oluşan bir referans kümesi ile karşılaştırılmasını sağlar. CCR ve BCC modellerinin birlikte çözülmesiyle, toplam teknik etkinlik skorunun (CCR), saf teknik etkinlik skoruna (BCC) oranlanmasıyla illerin ölçek etkinlikleri (Ölçek Etkinliği = CCR / BCC) de hesaplanabilmektedir (Erdoğan Aktan & Kaya Samut, 2013).

5. BULGULAR VE TARTIŞMA

Çalışmada ele alınan 20 ile ait girdi ve çıktı değişkenlerinin yapısını anlamak amacıyla ilk olarak betimsel istatistikler hesaplanmıştır. Girdi değişkenleri olarak işlenen tarım alanı (dekar) ve tarımsal mekanizasyon düzeyi (traktör ve tarım alet-ekipman sayısı); çıktı değişkenleri olarak ise sebze-meyve üretimi (ton) ile tahıl ve diğer bitkisel üretim miktarı (ton) kullanılmıştır. Tablo 2 de kullanılan değişkenler, Tablo 3 de ise bu değişkenlere ait ortalama, standart sapma, minimum ve maksimum değerleri göstermektedir.Çalışmada ele alınan 20 ile ait girdi ve çıktı değişkenlerinin yapısını anlamak amacıyla ilk olarak betimsel istatistikler hesaplanmıştır. Girdi değişkenleri olarak işlenen tarım alanı (dekar) ve tarımsal mekanizasyon düzeyi (traktör ve tarım alet-ekipman sayısı); çıktı değişkenleri olarak ise sebze-meyve üretimi (ton) ile tahıl ve diğer bitkisel üretim miktarı (ton) kullanılmıştır. Çıktıların parasal değer yerine fiziksel üretim miktarı (ton) cinsinden alınmasının nedeni, çalışmanın gıda arz güvenliği ve birim alandan elde edilen fiziksel verim odağıyla uyumlu olması ve fiziksel miktarın fiyat dalgalanmalarından bağımsız olarak tek bir kesit yılı için daha kararlı bir gösterge sunmasıdır. Tablo

2'de kullanılan değişkenler, Tablo 3'te ise bu değişkenlere ait ortalama, standart sapma, minimum ve maksimum değerleri göstermektedir.

Tablo 2: Girdi ve Çıktı Verileri (TÜİK)-2025

	GİRDİLER		ÇIKTILAR	
İLLER	TARIM ALANI (DEKAR)	TARIMSAL MEKANİZAS YON (ADET)	SEBZE MEYVE ÜRETİM (TON)	TAHIL VE DİĞER BİTKİSEL ÜRETİM (TON)
Adana	4920822	270511	3811225	2602241
Ankara	11211599	318906	1564487	2648328
Antalya	3280230	547939	6842772	1138673
Aydın	3677856	335926	1287913	3885977
Balıkesir	3900697	358524	1296042	4273338
Bursa	3048034	523897	3196931	3069739
Çanakkale	2879693	243032	1253405	3084796
Denizli	3762625	321260	995960	2568446
Diyarbakır	5447824	133392	469903	2193791
Hatay	2349963	182471	1901794	1021343
İzmir	3475000	474298	2979373	6244834
Karaman	3350183	145353	798834	2189611
Konya	18799614	722660	2219256	15752617
Manisa	5129455	608866	3138193	1583335
Mersin	3264267	348423	4824507	450088
Muğla	2016273	292006	1071045	1537767
Niğde	2760491	186402	709260	2096812
Ordu	2598213	96186	111608	75921
Samsun	3701918	373020	978525	2230479
Şanlıurfa	11132332	186187	865161	5035360

Tablo 2, analize konu olan 20 ile ait iki girdi (işlenen tarım alanı ve tarımsal mekanizasyon) ile iki çıktı (sebze-meyve üretimi ile tahıl ve diğer bitkisel üretim) değişkeninin il düzeyindeki ham değerlerini göstermektedir. Bu değerler, illerin tarımsal kaynak donanımı ve üretim hacmi bakımından birbirinden ne ölçüde farklılaştığını ortaya koymakta; söz konusu değişkenlere ilişkin merkezî eğilim ve dağılım ölçüleri ise Tablo 3'te gösterilmiştir.

Tablo 3: Girdi ve Çıktı Değişkenlerine İlişkin Betimsel İstatistikler

Değişken	**Ortalama**	**Standart Sapma**	**Minimum**	**Maksimum**
Tarım Alanı (Dekar)	5.035.354,45	4.097.644,39	2.016.273,00	18.799.614,00
Tarımsal Mekanizasyon (Adet)	333.462,95	169.192,12	96.186,00	722.660,00

Sebze-Meyve Üretimi (Ton)	2.015.809,70	1.676.758,92	111.608,00	6.842.772,00
Tahıl ve Diğer Bitkisel Üretim (Ton)	3.184.174,80	3.315.042,15	75.921,00	15.752.617,00

Betimsel istatistikler incelendiğinde, iller arasında tarımsal yapı ve üretim miktarları açısından çok ciddi bir heterojenlik olduğu görülmektedir. Tarım alanı değişkeninde Konya 18.799.614 dekar ile en yüksek değere sahipken, Muğla 2.016.273 dekar ile en düşük tarım alanına sahip ildir. Tarımsal mekanizasyon düzeyinde de benzer şekilde Konya 722.660 adet ekipmanla zirvede yer alırken, Ordu 96.186 adet ile en az mekanizasyona sahip birimdir. Çıktılar tarafında ise sebze ve meyve üretiminde Antalya 6.842.772-ton ile lider konumdayken, tahıl ve diğer bitkisel üretimde Konya 15.752.617-ton ile en yüksek üretim hacmine ulaşmıştır. Standart sapma değerlerinin yüksekliği, analiz kapsamındaki illerin ölçek ve üretim kapasitesi açısından geniş bir yelpazeyi temsil ettiğini ortaya koymaktadır.
Karar verme birimleri olarak belirlenen 20 ilin çıktı yönelimli CCR ve BCC modelleri çerçevesinde hesaplanan toplam teknik etkinlik, saf teknik etkinlik ve ölçek etkinliği skorları ile ölçeğe göre getiri durumları Tablo 4'ten takip edilebilir.

Tablo 4: İllerin Çıktı Yönelimli Etkinlik Skorları ve Ölçek Durumları

İl	**CCR (Teknik Etkinlik)**	**BCC (Saf Teknik Etkinlik)**	**Ölçek Etkinliği (SE)**	**Ölçeğe Göre Getiri**
Adana	1,0000	1,0000	1,0000	Sabit (CRS)
Ankara	0,4901	0,5272	0,9296	Azalan (DRS)
Antalya	1,0000	1,0000	1,0000	Sabit (CRS)
Aydın	0,7795	0,8362	0,9322	Artan (IRS)
Balıkesir	0,8049	0,8519	0,9449	Artan (IRS)
Bursa	0,7992	0,8729	0,9156	Artan (IRS)
Çanakkale	0,8574	1,0000	0,8574	Artan (IRS)
Denizli	0,5347	0,5702	0,9377	Artan (IRS)
Diyarbakır	0,7156	1,0000	0,7156	Artan (IRS)
Hatay	0,8021	1,0000	0,8021	Artan (IRS)
İzmir	1,0000	1,0000	1,0000	Sabit (CRS)
Karaman	0,8445	1,0000	0,8445	Artan (IRS)
Konya	1,0000	1,0000	1,0000	Sabit (CRS)
Manisa	0,4503	0,5121	0,8794	Azalan (DRS)
Mersin	1,0000	1,0000	1,0000	Sabit (CRS)
Muğla	0,4947	1,0000	0,4947	Artan (IRS)
Niğde	0,6946	1,0000	0,6946	Artan (IRS)
Ordu	0,0824	1,0000	0,0824	Artan (IRS)
Samsun	0,4250	0,4366	0,9735	Artan (IRS)
Şanlıurfa	1,0000	1,0000	1,0000	Sabit (CRS)
Ortalama	**0,7388**	**0,8804**	**0,8502**	**-**

Tablo 4'ten elde edilen bulgulara göre, 20 ilin çıktı yönelimli CCR modeline göre ortalama teknik etkinlik skoru 0,7388 olarak hesaplanmıştır. Bu değer, illerin mevcut girdi düzeylerini sabit tutarak tarımsal çıktılarını ortalama %35,35 oranında artırabileceğini göstermektedir. Esnek ölçek varsayımı altında çalışan BCC modelinde ise ortalama saf teknik etkinlik skoru 0,8804'e yükselmektedir. İllerin ortalama ölçek etkinliği (SE) ise 0,8502 olarak belirlenmiştir. Bu durum, Türkiye'deki tarımsal etkinsizliğin yaklaşık %12'sinin kaynakların yanlış yönetilmesinden (saf teknik etkinsizlik), %15'inin ise uygun olmayan işletme ölçeğinden (ölçek etkinsizliği) kaynaklandığına işaret etmektedir.Tablo 4'te yer alan bulgulara göre, 20 ilin çıktı yönelimli CCR modeline göre ortalama teknik etkinlik skoru 0,7388 olarak hesaplanmıştır. Bu skor düzeyi, illerin tam etkinliğe ulaşabilmeleri için mevcut girdilerini sabit tutarak çıktılarını ortalama olarak yaklaşık %35 (1/0,7388 - 1) düzeyinde artırmaları gerektiğine işaret etmektedir. Esnek ölçek varsayımı altında çalışan BCC modelinde ortalama saf teknik etkinlik skoru 0,8804'e yükselmekte, ortalama ölçek etkinliği (SE) ise 0,8502 olarak hesaplanmaktadır. Buna göre

ortalama saf teknik etkinsizlik yaklaşık %12 (1 - 0,8804), ortalama ölçek etkinsizliği ise yaklaşık %15 (1 - 0,8502) düzeyindedir; bu iki bileşen toplamsal değil, çarpımsal bir ilişkiyle (CCR = BCC × SE) birbirine bağlıdır.

Analiz edilen 20 il içinde Adana, Antalya, İzmir, Konya, Mersin ve Şanlıurfa hem CCR hem de BCC modellerine göre 1,0000 etkinlik skoruna ulaşarak tam etkin birimler olmuşlardır. Bu 6 il, tarımsal girdilerini en verimli şekilde çıktıya dönüştüren ve optimal ölçekte faaliyet gösteren 'referans iller' konumundadır.

Öte yandan Çanakkale, Diyarbakır, Hatay, Karaman, Muğla, Niğde ve Ordu illeri BCC modeline göre 1,0000 skoru ile saf teknik olarak etkin bulunurken, CCR modelinde etkinsiz çıkmışlardır. Bu durum, söz konusu illerde yönetsel bir etkinsizlik olmadığını, etkinsizliğin tamamen uygun olmayan üretim ölçeğinden (ölçek etkinsizliğinden) kaynaklandığını göstermektedir. Nitekim bu illerin tamamı "Artan Getiri (IRS)" bölgesinde yer almaktadır. Bu illerde tarımsal girdi miktarlarının oransal olarak artırılması, çıktılarda daha yüksek oranda bir artış sağlayacaktır.

Burada Ordu ve Muğla illerinin durumuna özel bir parantez açılması gerekmektedir. Ordu ili 0,0824 ve Muğla ili 0,4947 ölçek etkinliği skorları ile oldukça düşük performansa sahip olmalarına rağmen BCC modeline göre tam etkin (%100) bulunmuşlardır. VZA metodolojisinde, veri setindeki herhangi bir girdi değişkeninde en düşük değere sahip olan veya çıktı değişkeninde en uç değerde yer alan birimler, BCC modelinin konveksite kısıtı nedeniyle kendilerinden daha küçük bir referans birimi bulamadıkları için otomatik olarak etkin (saf teknik etkin) çıkmaktadırlar. Ordu'nun veri setindeki en düşük mekanizasyon düzeyine (96.186 adet) ve Muğla'nın en düşük tarım alanına (2.016.273 dekar) sahip olması, bu illerin BCC sınırında yer almasını açıklamaktadır. Ancak ölçek etkinlik skorları, bu illerin tarımsal üretimde son derece yetersiz ve etkinsiz bir ölçekte sıkışıp kaldığını açıkça ortaya koymaktadır.

Hem CCR hem de BCC modellerinde etkinsiz çıkan iller ise Ankara, Aydın, Balıkesir, Bursa, Denizli, Manisa ve Samsun'dur. Bu illerde tarımsal verimliliği artırmak için hem işletme ölçeğinin optimize edilmesi hem de kaynak kullanımındaki teknik/yönetsel aksaklıkların giderilmesi gerekmektedir. Özellikle Samsun saf teknik etkinlikte (0,4366) en düşük performansa, Manisa ise toplam teknik etkinlikte (0,4503) oldukça düşük seviyede kalmıştır.

Çıktı yönelimli VZA modelleri, girdileri sabit tutarak üretimin ne ölçüde artırılabileceğini belirlemektedir. Bu doğrultuda, etkinsiz bulunan 14 ilin mevcut girdileriyle ulaşabilecekleri potansiyel çıktı artış oranları Tablo 5'te sunulmuştur.

Tablo 5: Etkinsiz İllerin Potansiyel Çıktı Artış Oranları (%)

İl	CCR Modeline Göre Potansiyel Çıktı Artışı	BCC Modeline Göre Potansiyel Çıktı Artışı
Ankara	%104,05	%89,70
Aydın	%28,28	%19,59
Balıkesir	%24,23	%17,39
Bursa	%25,12	%14,57
Çanakkale	%16,63	%0,00
Denizli	%87,03	%75,38
Diyarbakır	%39,75	%-0,00
Hatay	%24,67	%0,00
Karaman	%18,41	%-0,00
Manisa	%122,07	%95,27
Muğla	%102,14	%0,00
Niğde	%43,98	%0,00
Ordu	%1114,22	%0,00
Samsun	%135,28	%129,04

Tablo 5 incelendiğinde, etkinsiz illerin mevcut kaynaklarını daha iyi yönetmeleri durumunda tarımsal çıktılarında çok ciddi artışlar sağlayabileceği görülmektedir. Örneğin Samsun ili, mevcut girdilerini değiştirmeden saf teknik etkinliğe ulaşarak sebze-meyve ile tahıl üretimini %129,04 oranında artırabilir. Benzer şekilde Manisa %95,27, Ankara ise %89,70 oranında bir çıktı artış potansiyeline sahiptir. Sadece ölçek etkinsizliği yaşayan illerden Ordu, ölçeğini optimize etmesi durumunda çıktısını %1114,22

(yaklaşık 12 kat), Muğla ise %102,14 oranında artırma potansiyeline sahiptir. Bu sonuçlar, Türkiye tarımında kaynakların fiziksel olarak artırılmasından ziyade, mevcut kaynakların kullanım biçiminin ve işletme ölçeklerinin düzenlenmesinin ne denli kritik bir öneme sahip olduğunu göstermektedir.

6. SONUÇ

Bu çalışma, Türkiye'de bitkisel üretim bakımından öne çıkan 20 ilin tarımsal üretim etkinliğini; işlenen tarım alanı ve mekanizasyon girdileriyle sebze-meyve ile tahıl ve diğer bitkisel çıktılar arasındaki ilişki üzerinden, çıktı yönelimli CCR ve BCC veri zarflama modelleriyle değerlendirmiştir. Bulgular, illerin önemli bir bölümünde göreli bir etkinsizlik bulunduğunu ve bu etkinsizliğin asıl kaynağının teknik ya da yönetsel aksaklıklardan çok uygun olmayan işletme ölçeği olduğunu ortaya koymaktadır. Nitekim ortalama toplam teknik etkinlik 0,7388 düzeyinde kalırken, saf teknik etkinlik ortalaması 0,8804'e yükselmekte; aradaki farkı açıklayan ortalama ölçek etkinliği ise 0,8502 olarak hesaplanmıştır. Bu tablo, sorunun büyük ölçüde kaynakların yanlış yönetilmesinden değil, üretimin etkin ölçeğin dışında gerçekleştirilmesinden kaynaklandığına işaret etmektedir.

İllerin etkinlik profilleri üç belirgin grupta toplanmaktadır. Adana, Antalya, İzmir, Konya, Mersin ve Şanlıurfa hem sabit hem değişken getiri varsayımı altında tam etkin bulunarak diğer iller için referans, yani en iyi uygulama konumundadır. Çanakkale, Diyarbakır, Hatay, Karaman, Muğla, Niğde ve Ordu yönetsel anlamda etkin olmakla birlikte ölçek etkinsizliği sergilemekte; tamamı artan getiri bölgesinde yer aldığından, bu illerde üretim ölçeğinin büyütülmesi çıktıda orantının üzerinde bir artış sağlayabilecektir. Ankara, Aydın, Balıkesir, Bursa, Denizli, Manisa ve Samsun ise hem ölçek hem de saf teknik etkinlik bakımından geride kalmakta; dolayısıyla bu illerde işletme büyüklüğünün ve kaynak kullanım biçiminin eşzamanlı olarak iyileştirilmesi gerekmektedir.

Elde edilen sonuçlar, tarım politikalarının iller arasındaki bu yapısal farklılıkları gözeten bir tasarımı gerektirdiğini göstermektedir. Ölçek etkinsizliğinin baskın olduğu ve artan getiri gösteren illerde, başta Ordu, Muğla ve Diyarbakır olmak üzere, öncelik; arazilerin miras ve satış yoluyla daha fazla bölünmesini sınırlayan düzenlemelere, arazi toplulaştırma çalışmalarının hızlandırılmasına ve üreticilerin ortak makine kullanımı ile kooperatifleşme yoluyla ölçek ekonomilerinden yararlanmasına verilmelidir. Bu çerçevede teşviklerin tek tip uygulanması yerine illerin getiri yapısına göre farklılaştırılması; artan getiri bölgelerinde kapasiteyi büyütmeye dönük, etkin ölçeğe ulaşmış illerde ise mevcut verimliliği koruyup derinleştirmeye dönük araçların önceliklendirilmesi daha tutarlı bir yaklaşım olacaktır.

Hem ölçek hem de saf teknik etkinlik bakımından geride kalan Samsun, Manisa, Ankara ve Denizli gibi illerde ise sorun yalnızca ölçekle açıklanamamakta; kaynak kullanımındaki teknik ve yönetsel zaaflar da belirleyici olmaktadır. Bu illerde üreticilerin modern üretim teknikleri, hassas tarım uygulamaları, sulama yönetimi ve gübre-ilaç kullanımının optimizasyonu konularındaki bilgi düzeyinin yükseltilmesi öncelik taşımaktadır. Özellikle mekanizasyon donanımı yüksek olmasına karşın etkinliği düşük kalan illerde makine parkının atıl kalmasını önleyecek kapasite planlamaları yapılmalı; nitelikli tohum ve girdi kullanımının yaygınlaştırılmasıyla birim alandan alınan verim artırılmalıdır. Böylece mevcut sermaye stoku, ek yatırım gerektirmeden daha üretken biçimde değerlendirilebilecektir.

Çalışmanın temel kısıtı, çıktıların parasal üretim değeri yerine fiziksel miktar (ton) üzerinden ölçülmüş olmasıdır. Bu tercih, fındık, çay ve süs bitkileri gibi tonajı düşük fakat katma değeri yüksek ürünlerde uzmanlaşan illeri olduğundan daha etkinsiz gösterebilmektedir; nitekim Ordu'nun belirgin biçimde düşük skoru büyük ölçüde bu ölçüm özelliğinin bir yansıması olup tümüyle yönetsel bir başarısızlık olarak okunmamalıdır. Bu nedenle çıktıların parasal değer üzerinden tanımlandığı, sulama ve gübre gibi ek girdilerin modele dâhil edildiği ve analizin zaman boyutuyla genişletildiği çalışmalar, sonuçların güvenilirliğini ve literatürle karşılaştırılabilirliğini artıracaktır. Bütün bu sınırlamalara karşın çalışma, Türkiye tarımında üretim artışının yeni kaynak aktarımından çok mevcut kaynakların etkin kullanımına ve işletme ölçeklerinin akılcı biçimde düzenlenmesine bağlı olduğunu ortaya koymakta; bu yönüyle bölgesel tarım politikalarının önceliklendirilmesine katkı sunmaktadır.

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THE IMPACT OF SOCIODEMOGRAPHIC FACTORS ON THE DEVELOPMENT OF ELECTRONIC COMMERCE

ELEKTRONİK TİCARETİN GELİŞİMİNDE SOSYODEMOGRAFİK FAKTÖRLERİN ETKİSİ

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Abstract
As technology advances and societies integrate into globalization, the importance and volume of electronic commerce continue to grow. The expansion of e-commerce enables individuals to diversify their needs and easily access desired products. The factors influencing e-commerce and its development have been examined by numerous researchers. This study also identifies the sociodemographic factors affecting the development of e-commerce through international examples. A global analysis is conducted by taking the findings of previous studies into consideration. The analysis reveals that sociodemographic determinants—such as age and generational cohort, gender, marital status, social environment, technological literacy and device ownership, income, education level, place of residence, time management and occupation—significantly impact the growth of e-commerce. The use of e-commerce varies according to age groups. Within the demographic structure, the dependent population shows less inclination toward e-commerce compared to the working population. While children face limitations due to a lack of digital literacy and device access, the elderly population is additionally influenced by traditional physical shopping habits. Regarding gender, differing product interests between men and women drive the e-commerce volume for specific product categories. In terms of marital status, the preferences of single individuals and married couples can vary based on individual versus shared product consumption. Furthermore, the social environment shapes product trends through interpersonal influence. E-commerce requires access to technological devices and a certain level of digital literacy. A substantial number of individuals lacking these resources poses an obstacle to the development of e-commerce. It is expected that high-income groups extensively use e-commerce, thanks to their access to adequate devices. Conversely, low-income groups allocate a significant portion of their budgets to physical shopping due to their consumption habits. The rate of e-commerce adoption also increases in parallel with individuals' education levels. Additionally, residing in urban or rural areas impacts e-commerce through accessibility factors. Professionals often face time management problems due to long working hours, which frequently leads them to e-commerce. Ultimately, e-commerce is influenced by dynamic variables. Since the technological advancements that form the infrastructure of e-commerce are continuous, the landscape of electronic commerce holds the potential to continually evolve over time.
Keywords: Electronic Commerce, Sociodemographic Factors, Consumer Behavior.

Özet
Teknolojinin gelişmesi ve toplumların küreselleşmeye entegre olması ile elektronik ticaretin önemi ve hacmi giderek artmaktadır. Elektronik ticaretin gelişimi, bireylere ihtiyaçlarını çeşitlendirme ve istediklerine erişebilme imkânı sunmaktadır. Elektronik ticaret ve gelişimini etkileyen faktörler birçok araştırmacı tarafından incelenmektedir. Bu çalışmada da elektronik ticaretin gelişiminde etkisi bulunan sosyodemografik faktörler uluslararası örnekler üzerinden belirlenmektedir. Konu ile ilgili yapılan geçmiş çalışmaların sonuçları da dikkate alınarak küresel boyutta bir inceleme yapılmaktadır. Yapılan incelemelere göre yaş ve kuşak durumu, cinsiyet, medeni durum, sosyal çevre, teknolojik aletlere ve bilgiye alaka ve sahiplik durumu, gelir düzeyi, eğitim düzeyi, yaşanılan yer, zaman tanzimi ve meslek gibi sosyodemografik belirleyicilerin elektronik ticaretin gelişiminde etkisi olduğu saptanmaktadır. Yaş

gruplarına göre elektronik ticaretin kullanımı farklılık göstermektedir. Nüfus yapısı içinde bağımlı grubun elektronik ticarete yatkınlığının çalışan nüfusa göre daha az olduğu görülmektedir. Çocuk yaş grubu, teknoloji kullanım bilgi ve alet eksikliği nedeniyle bu sorunu yaşarken, yaşlı nüfusta ise bunların yanında fiziki satın alım alışkanlığının bulunması da etkili olmaktadır. Cinsiyet açısından kadın ve erkek nüfus grubunun farklı ürünlere ilgi duyması, belirtilen ürünler bazında elektronik ticaret hacminin artmasını sağlamaktadır. Medeni durum açısından bekar bireyler veya evli çiftlerin bireysel ve ortaklaşa ürün kullanımı üzerinden tercihleri değişebilmektedir. Sosyal çevre, bireylerin birbirini etkilemesiyle ürün trendleri üzerinde etkili olmaktadır. Elektronik ticaret teknolojik alet ve belirli düzeyde kullanım bilgisine sahip olmayı gerektirir. Bu konuda eksikliği olan bireylerin fazlalığı elektronik ticaretin gelişimi önünde bir engel teşkil etmektedir. Yüksek gelir grubunun sahip olduğu donanımlar sayesinde elektronik ticareti fazlasıyla kullanması beklenen bir süreçtir. Düşük gelir grubu ise tüketim alışkanlıkları gereğince bütçelerinin önemli bir kısmını fiziksel alışverişle temin edilen ürünlere harcamaktadır. Eğitim düzeyinin yükseldiği bireylerin elektronik ticaret kullanma oranı da artmaktadır. Kırsal alanda veya kentte yaşamanın da elektronik ticaret üzerinde ulaşılabilirlik üzerinden etkisi bulunmaktadır. Meslek sahibi bireylerin yoğun çalışma saatleri nedeniyle zaman tanzimi sorunu yaşamaları onları sıklıkla elektronik ticarete yönlendirmektedir. Sonuç olarak elektronik ticaret dinamik değişkenlerden etkilenmektedir. Elektronik ticarete altyapı oluşturan teknolojik gelişimin süreklilik arz etmesi nedeniyle elektronik ticaretin de perspektifi zamanla değişme potansiyeli taşımaktadır.

Anahtar kelimeler: Elektronik Ticaret, Sosyodemografik Faktörler, Tüketici Davranışları.

İŞYERİNDE ÖTEKİLEŞTİRME: TÜRKİYE'DEKİ SURİYELİ VE ALMANYA'DAKİ TÜRK GÖÇMEN ÇALIŞANLARIN KARŞILAŞTIRMALI ANALİZİ VE BİR MODEL ÖNERİSİ

OTHERING IN THE WORKPLACE: A COMPARATIVE ANALYSIS OF SYRIAN MIGRANT WORKERS IN TÜRKİYE AND TURKISH MIGRANT WORKERS IN GERMANY, AND A PROPOSED MODEL

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ÖZET
Bu çalışma, işyerinde ötekileştirme olgusunu Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanlar ekseninde karşılaştırmalı ve teorik bir perspektiften ele alan kavramsal bir literatür taramasıdır. Göçmen işgücünün küresel ölçekte artan önemine karşın, göçmen çalışanların iş hayatındaki deneyimlerini bütünleşik bir çerçeve içinde açıklayan modellerin yazında sınırlı kaldığı görülmektedir. Çalışma bu boşluğa yanıt vermek amacıyla Tajfel ve Turner'ın Sosyal Kimlik Teorisi, Turner ve meslektaşlarının Öz-Kategorizasyon Teorisi ve Goffman'ın Damgalama Teorisi'ni tek bir kavramsal yapı altında bütünleştirmektedir. Seçilen bu iki ülke, salt coğrafi bir karşılaştırmanın ötesinde özgün bir teorik değer taşımaktadır; zira Türkiye, dünyanın en kalabalık mülteci nüfusuna ev sahipliği yaparken aynı zamanda tarihsel bir göç gönderen ülke konumunu sürdürmekte ve bu ikili rol karşılaştırmalı analiz için nadir bir zemin sunmaktadır. Karşılaştırmalı tarama, her iki grubun da etiketleme, dış-grup sınıflandırması ve kimlik tehdidi gibi özünde benzer ötekileştirme mekanizmalarıyla karşılaştığını; ancak bu mekanizmaların Türkiye'de hukuki güvencesizlik ve kayıt dışı istihdama yapısal sıkışma, Almanya'da ise kültürel ve dinsel kimlik üzerinden kuşaklar boyunca yeniden üretilen kurumsal dışlama biçiminde tezahür ettiğini ortaya koymaktadır. Çalışmanın özgün katkısı, bağlamsal etkenler, ötekileştirme süreci, kimlik tepkileri ve bireysel ile örgütsel çıktılardan oluşan dört bileşenli, döngüsel ve etkileşimli bir kavramsal modelin geliştirilmesidir. Önerilen model, bileşenler arasındaki ilişkilerin doğrusal olmadığını; çıktıların bağlamı yeniden şekillendirerek süreci beslediğini ve bağlamsal etkenlerin her aşamada düzenleyici bir rol üstlendiğini savunmaktadır. Böylece çalışma, gelecekteki ampirik araştırmalara sınanabilir ilişkiler öneren teorik bir yol haritası sunmayı amaçlamaktadır.
Anahtar kelimeler: İşyerinde Ötekileştirme, Göçmen Çalışanlar, Örgütsel Bağlılık, Türk Göçmenler, Suriyeli Göçmenler

ABSTRACT
This study is a conceptual literature review that examines the phenomenon of othering in the workplace from a comparative and theoretical perspective, focusing on Syrian migrant workers in Turkey and Turkish migrant workers in Germany. Despite the growing global significance of migrant labor, integrated frameworks that explain migrant workers' experiences in working life within a unified structure remain limited in the literature. To address this gap, the study integrates Tajfel and Turner's Social Identity Theory, Turner and colleagues' Self-Categorization Theory, and Goffman's Stigma Theory under a single conceptual framework. The two selected countries carry a distinctive theoretical value beyond a merely geographical comparison; for Turkey, while hosting the world's largest refugee population, simultaneously maintains its historical position as a migrant-sending country, and this dual role offers a rare basis for comparative analysis. The comparative review reveals that both groups encounter essentially similar mechanisms of othering—such as labeling, out-group categorization, and identity threat—yet these mechanisms manifest differently in each context: in Turkey, in the form of legal precarity and structural entrapment in informal employment, and in Germany, in the form of institutional exclusion reproduced across generations through cultural and religious identity. The study's

original contribution is the development of a four-component, cyclical, and interactive conceptual model comprising contextual factors, the othering process, identity responses, and individual and organizational outcomes. The proposed model argues that the relationships among its components are non-linear; that outcomes feed back into the process by reshaping the context; and that contextual factors assume a moderating role at every stage. The study thereby aims to offer a theoretical roadmap that proposes testable relationships for future empirical research.
Keywords: Workplace Othering, Migrant Workers, Conceptual Model, Turkish Migrants, Syrian Migrants

GİRİŞ

Küreselleşmenin ivme kazandığı ve zorunlu göçlerin tarihsel boyutlara ulaştığı günümüzde göçmen işgücü, hem gelişmiş hem de gelişmekte olan ekonomilerin vazgeçilmez bir bileşeni hâline gelmiştir. Uluslararası Çalışma Örgütü'nün (ILO) verilerine göre dünya genelinde çalışma çağındaki yaklaşık 168 milyon göçmen bulunmakta ve bu kişiler küresel işgücünün yaklaşık yüzde 4,7'sini oluşturmaktadır (ILO, 2024). Bu demografik gerçeklik, göçmenlerin iş hayatındaki deneyimlerini anlamayı salt bir akademik merak olmaktan çıkarmakta; örgütsel davranış, insan kaynakları yönetimi ve stratejik yönetim disiplinleri açısından öncelikli bir araştırma gündemine dönüştürmektedir (Hoppe & Fujishiro, 2025). Bununla birlikte, mevcut yazın incelendiğinde göçmen çalışanların iş hayatındaki deneyimlerini konu alan ampirik ve teorik çalışmaların oldukça sınırlı kaldığı görülmektedir. Nitekim son on yılda üst düzey örgütsel psikoloji dergilerinde yayımlanan çalışmaların göçmen işçilere odaklandığı; bu çalışmaların büyük çoğunluğunun ise nitel yöntemlere dayandığı tespit edilmiştir (Ornek, Weinmann, Waibel, & Radon, 2020). Bu veriler, alanın henüz olgunlaşma sürecinde olduğuna ve sistematik teorik çerçevelere olan ihtiyacın karşılanmadığına işaret etmektedir.

Göçmen çalışanların iş hayatında karşılaştığı en temel sorunların başında ötekileştirme gelmektedir. İşyerinde ötekileştirme; çalışanın etnik kökeni, dili, dini ya da göç statüsü temelinde dış-grup olarak sınıflandırılmasını, damgalanmasını ve sistematik biçimde dışlanmasını kapsayan çok katmanlı bir sosyal süreç olarak tanımlanmaktadır (Robinson, O'Reilly, & Wang, 2013). Bu süreç, yalnızca bireysel önyargının bir ürünü olmayıp; örgütsel pratikler, kurumsal düzenlemeler ve toplumsal söylemlerle iç içe geçerek yeniden üretilmektedir. Ötekileştirmenin örgütsel düzeydeki yansımaları ise son derece somuttur. Bunlar örgütsel bağlılık ve iş performansında azalma, işten ayrılma niyetinde ve üretim karşıtı davranışlarda yükselme bu sürecin başında gelmektedir. Bireysel düzeyde ise kimlik tehdidi, psikolojik refah kaybı ve toplumsal dışlanma duygusu öne çıkan sonuçlar olarak yer almaktadır (Gürlek, 2021). Tüm bu nedenlerle ötekileştirme hem örgütsel hem de toplumsal bütünleşme açısından kritik bir sorun alanı oluşturmaktadır.

Bu çalışma, söz konusu sorunsalı özgün ve karşılaştırmalı bir perspektiften ele almaktadır. Araştırmanın odak noktasını, birbiriyle teorik açıdan son derece verimli bir gerilim içinde bulunan iki göçmen grubu oluşturmaktadır. Bunlar Türkiye'deki Suriyeli göçmen çalışanlar ile Almanya'daki Türk göçmen çalışanlardır. Bu iki grubun bir arada incelenmesi, yalnızca coğrafi bir karşılaştırmanın ötesinde özgün bir teorik değer taşımaktadır. Zira Türkiye, dünya genelinde en fazla mülteci nüfusuna ev sahipliği yapan ülke konumundayken aynı zamanda tarihsel olarak Almanya başta olmak üzere pek çok Avrupa ülkesine işgücü ihraç eden bir kaynak ülke işlevi görmüştür (Akgündüz, 2021). Bu ikili konum, Türkiye'yi hem göçmen kabul eden hem de göçmen gönderen bir ülke olarak eş zamanlı biçimde konumlandırmaktadır. Nitekim bu çalışma göç yazınında karşılaştırmalı analiz için son derece nadir ve değerli bir bağlam sunmaktadır. İki grubun deneyimleri özünde benzer ötekileştirme mekanizmalarını barındırsa da göç türü, hukuki statü, kültürel mesafe ve tarihsel derinlik açısından birbirinden belirgin biçimde ayrışmaktadır. Suriyeliler için zorla göç ve geçici koruma statüsünün yarattığı yapısal kırılganlık belirleyiciyken, Almanya'daki Türkler için altmış yılı aşkın bir süreçte kuşaklar boyunca yeniden üretilen kültürel ve dinsel damgalama ön plana çıkmaktadır. Çalışmanın teorik çerçevesi üç temel kuram üzerine inşa edilmiştir. Bunlar Tajfel ve Turner'ın (2004) Sosyal Kimlik Teorisi, Turner ve meslektaşlarının (1987) Öz-Kategorizasyon Teorisi ve Goffman'ın (1986) Damgalama Teorisi'dir. Bu üç teorinin bütünleşik biçimde ele alınması, ötekileştirme sürecinin bilişsel, motivasyonel ve kurumsal boyutlarını aynı anda açıklamayı olanaklı kılmaktadır. Her bir teorinin tek başına karşılayamadığı açıklama boşluklarını kapatmaktadır. Söz konusu çerçeveye dayalı olarak çalışma, bağlamsal etkenler, ötekileştirme süreci, kimlik tepkileri ve çıktılar olmak üzere dört bileşenden oluşan özgün bir kavramsal model önerilmektedir. Model, bu bileşenler arasındaki ilişkilerin doğrusal değil döngüsel ve etkileşimli

bir yapı sergilediğini, bağlamsal etkenlerin sürecin yalnızca başlangıcında değil, her aşamasında düzenleyici bir rol üstlendiğini savunmaktadır.

Bu çerçevede çalışmanın üç temel amacı bulunmaktadır. Birincisi, Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanların işyerindeki ötekileştirme deneyimlerine ilişkin mevcut literatürü sistematik ve karşılaştırmalı biçimde derlemek ve değerlendirmektir. İkincisi, ötekileştirme sürecini açıklamada Sosyal Kimlik Teorisi, Öz-Kategorizasyon Teorisi ve Damgalama Teorisi'nin bütünleşik olarak nasıl kullanılabileceğini teorik düzeyde ortaya koymaktır. Üçüncüsü ise her iki bağlamı aynı çatı altında açıklayabilen, bireysel ve örgütsel çıktıları bütünleşik biçimde ele alan ve gelecekteki ampirik araştırmalara yol gösterecek özgün bir kavramsal model geliştirmektir.

TEORİK ÇERÇEVE

İşyerinde ötekileştirme olgusunu kavramsal düzeyde açıklamada başvurulacak ilk teorik zemin, Tajfel ve Turner'ın geliştirdiği Sosyal Kimlik Teorisi'dir. Sosyal Kimlik Teorisi, bireylerin benlik kavramlarını ait oldukları sosyal gruplara göre tanımladıkları ve bu aidiyetin benlik kimliğini koruyup pekiştirmeye hizmet ettiği temel önermesiyle başlamaktadır (Tajfel & Turner, 2004). Bu teori iç-grup ile dış-grup arasındaki sınır çizimini ve bireyin kendi grubuna olumlu yargıyla yaklaşma eğilimini bu sürecin ayrılmaz bileşenleri olarak ele almaktadır. Örgütsel bağlamda bu ayrım son derece belirleyici sonuçlar doğurmaktadır (Ashforth & Mael, 1989). Nitekim örgütsel hedeflere katkı isteği, örgütsel bağlılık ve düşük işten ayrılma niyetinin tümünün, bireyin örgütle kurduğu özdeşleşme düzeyiyle doğrudan ilişkili olduğu gösterilmiştir. Göçmen çalışanlar söz konusu olduğunda bu özdeşleşme süreci farklı bir boyut kazanmaktadır. Birey, hem köken kültürünün taşıyıcısı olarak kendi iç-grubuna hem de çalıştığı örgüte aynı anda aidiyet geliştirmeye çalışmaktadır. İki kimlik arasındaki gerilim ise ötekileştirmeye zemin hazırlayan temel dinamiği oluşturmaktadır (Williams & Liu, 2023). Nitekim Türkiye'deki Suriyeli göçmenler ile Almanya'daki Türk göçmenler, bu gerilimi farklı kurumsal ve kültürel bağlamlarda yaşamakla birlikte, özünde aynı kimlik tehdidiyle karşı karşıya kalmaktadır.

Sosyal Kimlik Teorisi'nin bilişsel süreçleri açıklama kapasitesini derinleştirmek amacıyla Turner ve meslektaşları (1987), Öz-Kategorizasyon Teorisi'ni geliştirmiştir. Öz-Kategorizasyon Teorisi, sosyal kimlik teorisinin gruplararası ilişkilerdeki motivasyonel ve dinamik boyutlarını esas alarak, bireylerin kendilerini ve başkalarını sosyal kategorilere yerleştirme sürecinin bilişsel mekanizmalarını açıklamaya odaklanmaktadır (Turner vd., 1987). Teorinin merkezindeki kişisellikten arınma kavramı, bireyin kendini bireysel özellikleri yerine grup üyeliğiyle tanımlaması sürecini ifade etmektedir. Turner ve meslektaşları bu sürecin benliğin yitirilmesi olmadığını, aksine benliğin grup üyeliği temelinde yeniden tanımlanması olduğunu vurgulamaktadır. Göçmen çalışanlar açısından bu durum çift yönlü bir baskı yaratmaktadır (Hogg & Terry, 2000). Bir yanda ev sahibi ülkenin baskın grubunun prototipiyle uyum beklentisi bulunurken, diğer yanda kültürel kimliğin belirgin kılındığı bağlamlarda göçmen, dış-grubun prototipi olarak konumlandırılmaktadır. Siyasi polarizasyonun yüksek olduğu bölgelerdeki örgütlerde göçmen çalışanların sosyal baltalanma süreçleri yaşadığı ve bu süreçlerin yüksek statülü bir kimlik edinmenin olanaklı olup olmadığına ilişkin sinyaller vererek çalışanların refahını doğrudan etkilediği ortaya konmuştur (Korman, Reinwald, Kunze, & Koos, 2025). Dolayısıyla öz-kategorizasyon süreci, ötekileştirmenin soyut bir sosyal ayrım olmanın ötesinde somut örgütsel sonuçlara nasıl dönüştüğünü açıklayan kritik bir bağ işlevi görmektedir.

Ötekileştirme sürecinin üçüncü teorik sacayağını, Goffman'ın (1986) Damgalama Teorisi oluşturmaktadır. Goffman'a göre damga, bireyin gerçek sosyal kimliği ile ona biçilen sanal sosyal kimlik arasındaki özel bir uçurumu ifade etmektedir. Bu uçurum bireyi toplumsal gözde tam ve olağan bir kişiden lekeli ve değersizleştirilmiş bir varlığa indirgemektedir (Goffman, 1986). Damgalama süreci dört ardışık aşamadan oluşmaktadır. Bunlar insan farklılıklarının etiketlenmesi, bu etiketlere olumsuz kültürel stereotiplerin iliştirilmesi, etiketlenen bireylerin prestijli gruplardan koparılarak ayrıştırılması ve nihayetinde bu bireylerin statü kaybı ile ayrımcılığa maruz bırakılması (Link & Phelan, 2001). Göçmen çalışanlar bağlamında damgalama, salt bireysel bir deneyim olmanın ötesinde kolektif ve örgütsel bir fenomene dönüşmektedir. Damgalamanın hedef bireylerle sınırlı kalmayıp onlara kaynak sağlayan kişi ve yapılara da sıçradığı, yani "ilişkilendirme yoluyla damgalama" biçiminde örgütsel sınırları aşabileceği vurgulanmaktadır (Pryor, Reeder, & Monroe, 2012). Türkiye'deki Suriyeli göçmenler için damganın temel kaynağını mülteci statüsü ve etnik köken oluştururken, Almanya'daki Türk göçmenler için din (Müslümanlık) ve etnik aidiyet, birbirleriyle kesişen damgalama eksenlerini meydana getirmektedir.

Söz konusu üç teorinin ayrı ayrı ele alınması, işyerinde ötekileştirme sürecinin bütüncül bir kavrayışını sağlamak açısından yetersiz kalmaktadır. Sosyal Kimlik Teorisi, iç-grup ve dış-grup ayrımının motivasyonel temelini açıklarken; Öz-Kategorizasyon Teorisi, bu ayrımın zihinsel düzeyde nasıl kurulduğunu ve hangi bağlamsal koşullar altında belirginleştiğini ortaya koymaktadır (Tajfel & Turner, 2004; Tajfel & Turner, 2004). Diğer taraftan Damgalama Teorisi ise bu bilişsel ve motivasyonel süreçlerin somut sosyal etiketlere ve kurumsal pratiklere nasıl dönüştüğünü açıklamaktadır (Goffman, 1986). Bu üç zeminin bağlantıları kurulduğunda, sosyal kimliklerin hem göçmenleri hem de ev sahibi toplumu etkilediği anlaşılmaktadır. Bu bütünleşik çerçevede ötekileştirme; kategori inşası yoluyla göçmenin dış-gruba yerleştirilmesini, kişisellikten arınma mekanizmasıyla bu yerleştirmenin içselleştirilmesini ve damgalama süreciyle kurumsal ve örgütsel zeminlere aktarılmasını kapsayan çok katmanlı bir süreç olarak tanımlanmaktadır (Stets & Serpe, 2013). Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanların deneyimleri, bu bütünleşik sürecin farklı kurumsal süreçler ve kültürel mesafeler altında nasıl tezahür ettiğini karşılaştırmalı biçimde inceleme olanağı sunmaktadır.

BAĞLAMSAL ANALİZ

Bu bölümde işyerinde ötekileştirme mekanizmalarını Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanlar ekseninde karşılaştırmalı olarak ele almaktadır. Türkiye'deki Suriyeliler geçici koruma statüsü ve kayıt dışı istihdamın yarattığı yapısal kırılganlık içinde çalışırken (Badalič, 2023; Saraçoğlu & Bélanger, 2025), Almanya'daki Türk göçmenler 1961'den bu yana süregelen ve etnik ile dinsel kimlik üzerinden işleyen kuşaklar arası bir ötekileştirme deneyimi yaşamaktadır (Koopmans, 2016). Her iki grup özünde benzer dışlama mekanizmalarıyla karşılaşmakla birlikte, bu mekanizmaların tetikleyicileri ve kurumsal zeminleri birbirinden belirgin biçimde ayrışmaktadır.

Türkiye'deki Suriyeli Göçmen Çalışanlar

Türkiye'deki Suriyeli göçmenlerin iş hayatındaki konumunu belirleyen en temel yapısal etken, bu grubun hukuki statüsüdür. 2013 yılında yürürlüğe giren Yabancılar ve Uluslararası Koruma Kanunu (YUKK) çerçevesinde Suriyelilere "geçici koruma" statüsü tanınmıştır (Özel, 2020). Ancak bu statü, tam anlamıyla mülteci statüsünün sağladığı uzun vadeli güvencelerden yoksun olup vatandaşlığa giden yolu açık tutmamaktadır. Geçici koruma statüsü biçimsel istihdama erişimin önünde ciddi engeller oluşturmaktadır (Şahin Emir, 2021). Bu durum yaygın kayıt dışı çalışmaya, düşük ücretlere, kötü çalışma koşullarına ve sınırlı hukuki korumaya yol açmaktadır. Çalışma izni sisteminin 2016 yılında hayata geçirilmesiyle birlikte bir ilerleme kaydedilmiş olsa da uygulamada sonuçlar sınırlı kalmıştır. Yaklaşık bir milyon Suriyelinin hukuki güvenceden yoksun biçimde kayıt dışı çalıştığı tahmin edilmektedir (Yıldız & İzmirlioglu, 2022). Çalışma izninin işverenin başvurusuna bağlı olması, çalışanı işverenin insafına terk eden asimetrik bir güç ilişkisi doğurmaktadır. Bu durum Suriyelilerin örgütsel düzeyde ötekileştirilmesine zemin hazırlayan yapısal bir kırılganlık unsuru olarak işlev görmektedir. Nitekim kayıt dışı ekonomiyle ilgili teorileri göçmen çalışan verisiyle harmanlayan araştırmalar, Suriyeli işçileri kayıt dışılığa iten faktörler arasında bürokratik engelleri, işçi olarak sağlanan parasal ve parasal olmayan avantaj algısını, iş mevzuatına ilişkin bilgisizliği ve sınır dışı edilme korkusunu öne çıkarmaktadır (Özel, 2020; Şahin Emir, 2021).

Türkiye'deki yüksek kayıt dışılık oranı, Suriyeli göçmenlerin iş hayatındaki ötekileştirme sürecini yalnızca bireysel bir deneyim olmaktan çıkararak yapısal bir boyuta taşımaktadır. Kayıt dışı ekonominin Türkiye ekonomisinin yaklaşık üçte birini oluşturduğu tahmin edilmektedir. Suriyeliler ise yasal haklara sahip olmaksızın, sömürüye açık, düşük ücretli ve fiziksel açıdan ağır işlerde çalışmaya mecbur kalmaktadır. Araştırmalar, bu koşulların somut ayrımcı sonuçlar ürettiğini ortaya koymaktadır (Badalič, 2023). Türk yerel çalışanlarıyla karşılaştırıldığında, Suriyeli mültecilerin ortalama olarak haftada kayıtlı yerli işçilerden yaklaşık beş saat fazla mesai yaptığı ve çalışanların yarısından fazlasının haftalık 50 saatin üzerinde çalıştığı görülmektedir. Kayıt dışı istihdam, yalnızca aşırı çalışma saatleri aracılığıyla değil, örgütsel düzeyde de ötekileştirici mekanizmalar üretmektedir. Kayıt dışı statü, göçmen çalışanı şikâyet mekanizmalarından, sosyal güvenlik haklarından ve sendikacılık olanaklarından mahrum bırakmaktadır (Mohammed, 2024). Böylece onu örgütsel yelpazenin görünmez ama vazgeçilmez bir dış-grubu olarak konumlandırmaktadır. Nitekim İstanbul'daki tekstil sektöründe çalışan Suriyelilerle yürütülen nitel araştırmalar, bu "hiper güvencesizlik" durumunun yalnızca maddi refahı değil, bireylerin öz-kontrol algısını ve psikolojik bütünlüğünü de derinden sarstığını ortaya koymuştur (Erol, ve diğerleri, 2023).

Hukuki ve ekonomik yapıların ötesinde, Suriyeli göçmen çalışanlar işyerlerinde simgesel ve kişilerarası düzeyde de ötekileştirme pratikleriyle karşılaşmaktadır. Dil engeli, bu pratiklerin hem tetikleyicisi hem de sürdürücüsü olarak öne çıkmaktadır. Türkçe bilmeyen Suriyeli mülteciler, çalışabilecekleri sektörler açısından ağır biçimde kısıtlanmaktadır. Bu durum işgücünü tekstil, inşaat ve tarım gibi yoğun kayıt dışılığın hâkim olduğu alanlarda yoğunlaştırmaktadır (Lordoğlu & Aslan, 2016). Dil yetersizliği, söz konusu çalışanların etnik kimliklerini sürekli görünür kılmakta ve onları Goffman'ın kavramıyla "damgalanmış" statüsüne taşımaktadır (Goffman, 1986). Damganın salt bireysel bir etiketleme olmanın ötesinde kurumsal bir işleyiş kazandığını gösteren bulgular da dikkat çekicidir. Yükselen göçmen karşıtı söylemin yerel şirketleri Suriyeli işçi istihdam etmekten caydırdığı, ev sahiplerinin Suriyelilere mülk kiralamayı reddettiği ifade edilmektedir. Knappert, Kornau ve Figengül'ün (2018) Türkiye-Suriye sınırındaki atölye çalışmalarına dayanan araştırması ise bu damganın işyerinde nasıl olduğunu göstermektedir. Çalışma Suriyeli çalışanların çalışma ortamlarında dışlanma, istismar ve hayal kırıklığı hissettiklerini dile getirdiğini ortaya koymaktadır (Knappert, Kornau, & Figengül, 2018). Bu bulgular, etnik köken ve mülteci statüsünün iç içe geçtiği kesişimsel bir damgalama örüntüsüne işaret etmektedir. Türkiye'deki Suriyeli göçmen çalışanlara ilişkin ampirik literatür, ötekileştirme sürecinin ekonomik, mekânsal ve psiko-sosyal boyutlarını birlikte belgelemektedir. Sektörel dağılım açısından değerlendirildiğinde, mültecilerin büyük çoğunluğunun imalat sektöründe, ağırlıklı olarak tekstil sanayiinde, inşaat ile ticaret ve konaklama sektörlerinde istihdam edildiği görülmektedir. Bu çalışanlar uzun mesai saatleri, asgari ücretin altında ödeme ve yüksek iş kazası riski gibi koşullarla mücadele etmek zorunda kalmaktadır. Ücret farklılıkları açısından ise mevcut araştırmalar sistematik bir ayrımcılık örüntüsü ortaya koymaktadır. İstanbul'da yaşan Suriyeli işçiler ile işverenlerden toplanan verilere dayanan araştırma, ücret-verimlilik farkı ile algılanan ekonomik ve sosyal ayrımcılık arasında anlamlı bir ilişki bulunduğunu, farkın büyüdükçe ayrımcılık algısının da derinleştiğini ortaya koymuştur (lgin & Elveren, 2024). Sosyal mesafe boyutunda ise Suriyeli işçilerin; yerli işçilerin artık çalışmak istemediği, düşük ücretli işlere yönlendirildiği görülmektedir. Bu durum emek piyasasında onlara biçilen dış-grup rolünü ekonomik düzlemde de somutlaştırmaktadır (Acun & Kahveci, 2022). Tüm bu bulgular bir arada değerlendirildiğinde, Türkiye'deki Suriyeli göçmen çalışanların ötekileştirilmesinin tek boyutlu bir ayrımcılık olmadığını; hukuki statü, kayıt dışı ekonomi, etnik damgalama ve sosyal mesafe gibi birbirini besleyen mekanizmaların bir araya geldiği çok katmanlı bir süreç olduğu anlaşılmaktadır.

Almanya'daki Türk Göçmen Çalışanları

Almanya'daki Türk göçmen çalışanların iş hayatındaki konumunu ve ötekileştirilme deneyimlerini anlayabilmek için bu grubun yaklaşık altmış yıllık emek tarihini kavramak gerekmektedir. İkinci Dünya Savaşı'nın ardından Almanya'nın yaşadığı ekonomik döneminde artan işgücü talebini karşılamak amacıyla yabancı işçi istihdamına yönelen Batı Almanya, 1961 yılında Türkiye ile ikili bir işgücü anlaşması imzalamıştır. 1973 yılına gelindiğinde Türk çalışanlar toplam yabancı nüfusun üçte birini oluşturarak ülkedeki en büyük göçmen grubu konumuna yükselmiştir (Abadan-Unat, 2024). Misafir işçi olarak tanımlanan bu çalışanlar, başlangıçta geçici bir işgücü olarak konumlandırılmıştır. Almanya'daki iş çevresi ise onları ekonomik bir araç olarak kabul ederken sosyal entegrasyon yolları büyük ölçüde kapalı tutulmuştur (Castles & Kosack, 1973).

Dönemin ilk nesil işçileri bu durumu bizzat dile getirmiş, Almanya'nın kendilerini bütünleştirmek gibi bir niyeti olsaydı dil kursları veya kültürel hazırlık programları sunacağını, oysa hiçbir destek verilmeksizin tanımadıkları bir çevreyle baş başa bırakıldıklarını ifade etmişlerdir (Glitz, 2014). "Misafir" olarak çağrılan ama kalıcı olarak yerleşen bu işgücü, kuşaklar boyunca aktarılan yapısal bir ötekileştirmenin başlangıç noktasını oluşturmuştur. Sanayi üretimin baskın olduğu dönemden bu yana Almanya'da yaşanan makro-yapısal dönüşümlerin birinci nesil Türk erkek işçilerle yerli Almanlar arasındaki istihdam ve gelir uçurumunu 1970'lerden 2010'lara uzanan süreçte kayda değer biçimde derinleştirdiği görülmektedir (Abadan-Unat, 2024).

Türk göçmen çalışanların Alman iş piyasasındaki ötekileştirilmesi, bireysel önyargının çok ötesinde, yapısal ve kurumsal mekanizmalar aracılığıyla yeniden üretilmektedir. Tüm misafir işçi kökenli gruplar arasında Türk kökenli göçmenler, yalnızca yerel Almanlarla değil diğer misafir işçi gruplarıyla karşılaştırıldığında da daha yüksek işsizlik oranları, daha düşük gelir düzeyi ve daha düşük mesleki prestij puanlarıyla birbirini kilitleyici biçimde pekişen dezavantajlar sergilemektedir (Wiedner & Giesecke, 2022). Bu dezavantaj yalnızca ilk nesle özgü değildir. Araştırmalar ikinci kuşağın da benzer

engellerle karşılaştığını ortaya koymaktadır. Almanya'da Türk göçmenlerin yerlilerle karşılaştırıldığında istihdam oranlarının daha düşük olduğu, güvenceli iş oranları ile mesleki prestij puanlarındaki uçurumun ise büyük ölçüde yapısal nitelik taşıdığı saptanmıştır (Kaas & Manger, 2012). İşe alım sürecindeki ayrımcılık boyutunda ise saha deneylerinden elde edilen bulgular çarpıcı niteliktedir. Türk kökenli iş başvurularının eşdeğer niteliklere sahip olmalarına karşın, yerli adaylarla karşılaştırıldığında ortalama olarak yüzde on bir daha az olumlu geri dönüş aldığı belgelenmiştir (Glitz, 2014). Terfi süreçlerindeki cam tavan olgusunu belgeleyen araştırmalar ise ücret eşitsizliğinin kariyer basamaklarında da sürdüğüne işaret etmektedir. Ortaöğretim ya da yükseköğretim düzeyinde eğitim almış istihdam edilmiş Türk göçmenlerin dahi, aynı eğitim düzeyindeki yerli akranlarının gerisinde kaldığı, bu durumun eğitimin ötesinde ayrımcılık kaynaklı bir etnik ceza işleyişine işaret ettiği görülmektedir (Hartmann, 2016).

Almanya'daki Türk göçmen çalışanların ötekileştirilmesi, yalnızca yapısal eşitsizliklerle değil kültürel ve dinsel kimliğin işyerinde ayrımcılık aracına dönüştürülmesiyle de kendini göstermektedir. Bu bağlamda en kapsamlı biçimde belgelenen olgu başörtüsü ayrımcılığıdır. Damgalama, sosyal kimlik ve kesişimsel ayrımcılık teorilerine dayanan saha çalışmaları Almanya'da Türk kökenli kadınların iş başvurularında mülakat davetine daha az davet edildiğini, başörtüsü takılması durumunda bu ayrımcılık düzeyinin önemli ölçüde arttığını ortaya koymuştur (Weichselbaumer, 2020). Nitekim bu bulgu sayısal olarak da somutlaştırılmıştır. Türk adlı ve başörtülü bir kadın adayın aynı sayıda mülakat daveti alabilmek için Alman adlı ve başörtüsüz bir adaya kıyasla daha fazla başvuru yapması gerekmektedir. Dinsel kimliğin ötekileştirici bir işlev kazanması, salt başörtüsüyle sınırlı kalmayıp işyerinin gündelik pratiklerine de sızmaktadır (Kaas & Manger, 2012).

Ramazan orucunun tutulması, Cuma namazı için kısa aralar talep edilmesi ya da Kurban Bayramı gibi dinî tatiller konusundaki esneklik beklentisi, Türk çalışanlar için makul uyum hakkını pratikte zorlaştırmaktadır. Alman iş piyasasında gerçekleştirilen ve 50.000'den fazla başvuruyu kapsayan kapsamlı alan araştırmasında, başvuru sahibinin adının Arapça ya da Türkçe olmasının, niteliklerden bağımsız biçimde, işverenlerden anlamlı ölçüde daha az yanıt alınmasına yol açtığını ortaya koymuştur (Köhler & Wiemann, 2025). Bu bulgular, ilk Türk göç dalgasının üzerinden altmış yılı aşkın süre geçmiş olmasına karşın ırkçılık ve ayrımcılığın Alman toplumunda derin izler bıraktığının ölçülebilir bir göstergesi olduğunu destekler niteliktedir.

Almanya'daki Türk göçmen çalışanlara ilişkin literatür, ötekileştirme deneyiminin kuşaktan kuşağa farklılaştığını ve kurumsal koruma mekanizmalarının bu süreci kısmen dönüştürdüğünü ortaya koymaktadır (Wiedner & Giesecke, 2022). Kuşaklar arası farklılıklar açısından, eski misafir işçilerin erken kuşakları için istihdam farklarının nesiller boyunca derinleştiği doğrulanmakla birlikte, daha geç dönemde gelen Türk göçmenler için daha olumlu gelişmelerin gözlemlendiği bulunmuştur. İkinci kuşak açısından ise tablo daha karmaşık bir görünüm arz etmektedir (Hartmann, 2016). Grup düzeyinde ayrımcılık algısının ikinci kuşak göçmenler arasında işsizlikle güçlü biçimde ilişkili olduğu belirtilmektedir. Beşeri sermaye, göç geçmişi, dindarlık, kültürel değerler ve ayrımcılık algısının Müslümanlar ile Müslüman olmayanlar arasındaki istihdam farklılığının yalnızca yüzde kırkını açıklayabildiği ifade edilmektedir (Connor & Koenig, 2015). Bu durum ayrımcılığın bireysel düzeyde açıklanamayan yapısal bir boyutu olduğuna işaret etmektedir.

Kurumsal koruma mekanizmaları açısından ise Almanya'nın 2006 yılında yürürlüğe giren Genel Eşit Muamele Yasası, etnik köken, din ve cinsiyet temelinde ayrımcılığı yasaklayan önemli bir hukuki güvence oluşturmuştur. Bununla birlikte, Almanya'da Türk göçmen çalışanlar üzerinde yürütülen araştırmalar, kapsayıcı ve açık bir işyeri ikliminin bu grubun örgütsel bağlılığı, çalışma motivasyonu ve ruh sağlığı üzerindeki olumsuz göç etkisini hafiflettiğini, yasal güvencelerin ancak örgütsel iklim değişkenleriyle birleştiğinde anlamlı bir fark yarattığını ortaya koymuştur (Ulusoy vd., 2016). Bu bulgular, kurumsal düzenlemelerin tek başına yeterli olmadığını kâğıt üzerindeki eşitlikten işyerinde yaşanan gerçek kapsayıcılığa geçişin, örgütsel kültür ve liderlik pratikleri tarafından şekillendirildiğini göstermektedir.

KARŞILAŞTIRMALI LİTERATÜR TARAMASI

Ötekileştirme Süreci: Mekanizmalar, Bağlamlar ve Temel Farklılıklar

Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanların ötekileştirme deneyimleri karşılaştırmalı biçimde ele alındığında, sürecin her iki bağlamda da benzer mekanizmalar aracılığıyla işlediği ancak tetikleyici etmenlerin ve kurumsal zeminlerin belirgin biçimde ayrıştığı görülmektedir.

Her iki grupta da ötekileştirme; dış-grup etiketlemesi, damgayla bütünleşik dışlama pratikleri ve kimlik tehdidi biçiminde tezahür etmektedir. Bununla birlikte, sürecin yapısal kökenleri farklılaşmaktadır (Baban, Ilcan, & Rygiel, 2017). Türkiye bağlamında ötekileştirmenin birincil kaynağını geçici koruma statüsünün yarattığı hukuki güvencesizlik ve kayıt dışı ekonomiye yapısal sıkışma oluştururken, Almanya'da onlarca yıl önce gerçekleşen ilk göç dalgasına karşın Türk ve Arap kökenli bireylerin eğitimden bağımsız biçimde ayrı bir kategoride tutulduğu ve sistematik kariyer ayrımcılığına maruz kaldığı belgelenmiştir (Kaas & Manger, 2012; Wiedner & Giesecke, 2022). Öte yandan, her iki bağlamda da siyasi atmosferin ötekileştirmeyi derinleştiren bir çarpan işlevi gördüğü anlaşılmaktadır.
Siyasi yapılanma ve aşırı sağ seçmen desteğinin yüksek olduğu bölgelerdeki örgütlerde göçmen çalışanların sosyal baltalanma süreçleri yaşadığı, bu dinamiklerin ise göçmenin yüksek statülü bir kimlik elde edip edemeyeceğine ilişkin sinyaller vererek refah düzeyini doğrudan etkilediği görülmektedir (Korman, Reinwald, Kunze, & Koos, 2025). Türkiye'deki yükselen göçmen karşıtı söylem ile Almanya'daki aşırı sağın güçlenmesi, bu yapısal benzerliğin iki farklı ulusal bağlamdaki yansımaları olarak değerlendirilebilir. Karşılaştırmalı literatürün ortaya koyduğu kritik fark şudur; Suriyeli göçmenler için ötekileştirme büyük ölçüde hukuki statünün doğrudan bir ürünüyken, Türk göçmenler için bu süreç daha çok kültürel-dinsel kimliğin hem görünür hem de görünmez bir damgaya dönüştürülmesi yoluyla gerçekleşmektedir (Weichselbaumer, 2020; Baban, Ilcan, & Rygiel, 2017; Kaas & Manger, 2012).

Bireysel Sonuçlar: Kimlik Tehdidi, Psikolojik Refah ve Uyum Stratejileri

Ötekileştirme sürecinin bireysel düzeydeki sonuçları incelendiğinde, her iki bağlamda da kimlik tehdidinin merkezi bir değişken olarak öne çıktığı görülmektedir. Ancak bu tehdidin biçimi ve bireyin buna verdiği tepkiler farklılaşmaktadır. Sosyal statü kaybı, ayrımcılık ve aile bağlarından kopuş bu riskleri belirgin biçimde artıran başlıca etkenler arasında yer almaktadır. Türkiye'deki Suriyeli çalışanlara ilişkin araştırmalar, ötekileştirmenin bireysel düzeyde nasıl içselleştirildiğini gözler önüne sermektedir. İşyerinde dışlanma ile üretim karşıtı davranışlar arasındaki ilişkinin yoğunluğu, kültüre göre farklılaşmaktadır (Gürlek, 2021). Köken kültürünü muhafaza edenlerde bu ilişki güçlenirken ev sahibi kültürle bütünleşenlerde zayıflamaktadır (Knappert, Kornau, & Figengül, 2018). Bu bulgu, kimlik tehdidine karşı geliştirilen uyum stratejisinin bireysel refahın hem belirleyicisi hem de koruyucusu olarak işlev gördüğünü ortaya koymaktadır.
Almanya'daki Türk göçmenler söz konusu olduğunda ise kimlik tehdidinin daha karmaşık ve çok kuşaklı bir görünüm kazandığı görülmektedir. Almanya'daki Türk göçmen çalışanların örgütsel bağlılık, çalışma motivasyonu ve ruh sağlığı üzerindeki olumsuz göç etkisinin, kapsayıcı ve açık bir işyeri ikliminin varlığıyla önemli ölçüde hafifleyebildiği saptanmıştır (Wiedner & Giesecke, 2022). Bireysel uyum stratejileri açısından, marjinalleşme stratejisinin her iki bağlamda da en olumsuz sonuçları doğurduğunu ortaya koymaktadır. Marjinalleşme stratejisini benimseyen göçmen çalışanlar, hem köken hem de ev sahibi kültürden destek görmeksizin her iki toplumsal çevreden dışlandıklarından, düşük örgütsel bağlılık ve yüksek işten ayrılma niyetiyle karşı karşıya kalmaktadır (Baban, Ilcan, & Rygiel, 2017). Bununla birlikte, Suriyeli göçmenlerin psikolojik kırılganlıklarının yapısal boyutunun (zorla göç, geçici statü belirsizliği, geri dönüş kaygısı, vs.) Almanya'daki Türk göçmenlerinkinden nitelik olarak ayrıştığı ve bu farkın teorik açıdan da kayda değer olduğu anlaşılmaktadır.

Örgütsel Sonuçlar: Bağlılık, Performans ve Üretim Karşıtı Davranış

Ötekileştirmenin örgütsel düzeydeki sonuçları değerlendirildiğinde, literatürün birbiriyle bağlantılı üç temel çıktı etrafında yoğunlaştığı görülmektedir. Bunlar örgütsel bağlılık, iş performansı ve üretim karşıtı davranışlardır (Robinson, O'Reilly, & Wang, 2013). Bu üç çıktı, ötekileştirme deneyiminin şiddetine ve bireyin benimsediği uyum stratejisine bağlı olarak farklı biçimler almaktadır. Göçmen çalışanların işyerindeki karşılaştığı sıkıntılar psikolojik refahı, örgütsel özdeşleşmeyi ve iş performansını doğrudan olumsuz etkilemektedir (Gürlek, 2021). Öte yandan bu süreçler örgütsel başarı ve iş gücü tutunumu açısından da kritik bir belirleyici olduğu ortaya konulmuştur. Örgütsel bağlılık boyutunda her iki bağlamdan elde edilen bulgular örtüşmektedir. Ötekileştirme durumunun artması, duygusal bağlılığı aşındırarak araçsal ya da normatif bağlılığa geçişi hızlandırmaktadır (Ulusoy, ve diğerleri, 2016; Robinson, O'Reilly, & Wang, 2013).
Üretim karşıtı davranışlar söz konusu olduğunda ise bulgular daha farklı bir tablo ortaya koymaktadır. Örgütsel özdeşleşmenin sağlanamaması durumunda kimlik kaygısının bilişsel ve duygusal kaynakları tükettiği ve bunun üretim karşıtı davranışlara zemin hazırladığı görülmektedir. Bu nedenle örgütlerin

yalnızca adil ücret ve çalışma ortamı sağlamakla yetinmeyip geçici ya da dışlanmış çalışanlar arasında örgütsel özdeşleşmeyi aktif olarak desteklemesi gerekmektedir (Ashforth & Mael, 1989). İş performansı açısından ise son on yılda üst düzey örgütsel psikoloji dergilerinde göçmen çalışanlar üzerine yayımlanan ampirik çalışmaların oldukça sınırlı kaldığı ve mevcut araştırmaların büyük çoğunluğunun nitel yöntemlere dayandığı görülmektedir. Çalışmaların ağırlıklı olarak mülteci kariyer ilerlemesi ve kariyer uyum süreçlerine odaklandığı anlaşılmaktadır (Erol, ve diğerleri, 2023;Badalič, 2023). Bu saptama, her iki bağlamı kapsayan karşılaştırmalı nicel araştırmaların sınırlı kaldığına işaret etmekte ve mevcut literatür taramasının özgün katkısını somutlaştırmaktadır.

Türkiye'deki Suriyeli ve Almanya'daki Türk göçmen çalışanlarına ilişkin karşılaştırmalı literatür taraması, iki grup arasındaki hem yapısal benzerlikleri hem de köklü farklılıkları gün yüzüne çıkarmaktadır. Benzerlikler açısından değerlendirildiğinde, her iki grubun da dış-grup statüsüne yerleştirme, etnik damgalama ve kimlik tehdidi gibi özünde aynı ötekileştirme mekanizmalarına maruz kaldığı görülmektedir (Goffman, 1986; Link & Phelan, 2001). Her iki bağlamda da ayrımcılık bireysel psikolojik refah ve örgütsel bağlılık üzerinde belirgin olumsuz etkiler doğurmakta, siyasi kutuplaşma ise bu etkileri güçlendiren ortak bir bağlamsal değişken olarak karşımıza çıkmaktadır (Korman, Reinwald, Kunze, & Koos, 2025; Ulusoy, ve diğerleri, 2016).

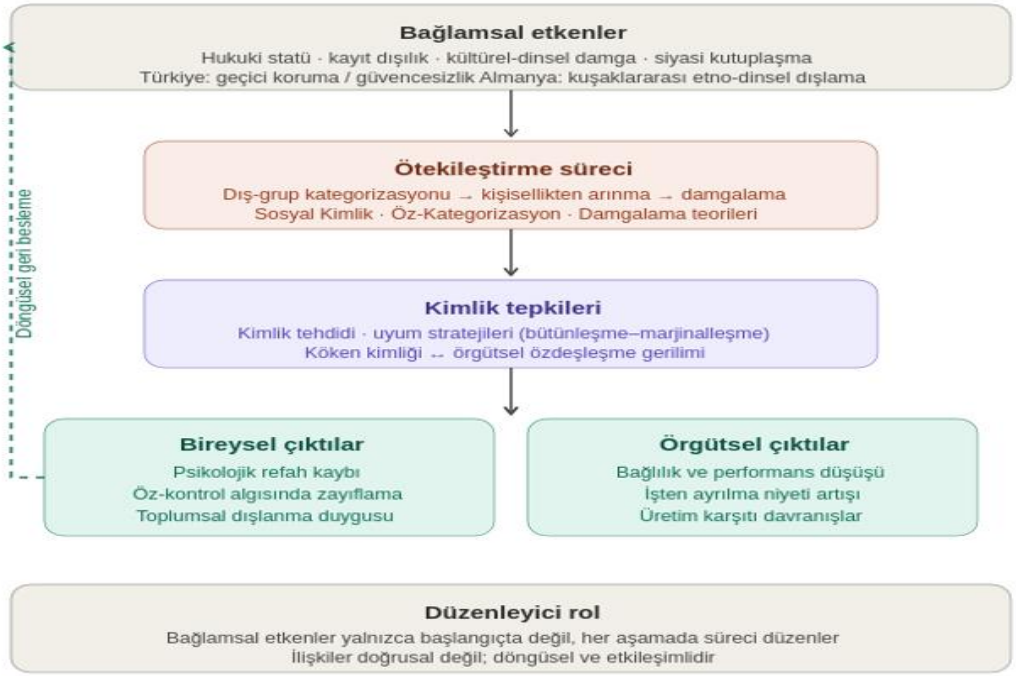
Farklılıklar açısından ise tablo daha karmaşık bir görünüm arz etmektedir. Suriyelilerin durumu hukuki güvencesizlik ve yapısal kayıt dışılık tarafından biçimlendirilirken, Türk göçmenlerin deneyimi kültürel-dinsel kimliğin kurumsal ayrımcılığa dönüştüğü köklü ve kuşaklar arası bir süreç olarak kendini göstermektedir (Baban, Ilcan, & Rygiel, 2017; Şahin Emir, 2021; Badalič, 2023). Kolektivist kökenli göçmenlerin bireyci ev sahibi ülkelerde ödüller açısından dezavantajlı konumda bulunduğu anlaşılmaktadır. Bu durumun salt eğitim ya da beceri farklılıklarıyla değil kültürel uyumsuzluğun örgütsel ödül sistemlerine yansımasıyla da ilişkili olduğu görülmektedir (Hartmann,2016; Weichselbaumer, 2020). Bu bulgu hem Suriyeli hem de Türk göçmen çalışanlar için geçerliliğini korumakla birlikte Türkiye bağlamında kültürel mesafenin görece kısa olması nedeniyle farklı biçimlerde tezahür etmektedir (Badalič, 2023; Mohammed, 2024). Teorik boşluklar açısından ise mevcut literatür üç önemli eksikliği barındırmaktadır. Bunlar karşılaştırmalı çok düzeyli tasarımların yetersizliği; hem bireysel hem örgütsel sonuçları aynı anda kapsayan bütünleşik modellerin sınırlılığı ve Türkiye gibi hem göçmen gönderen hem de kabul eden bir ülkeyi merkeze alan araştırmaların neredeyse yokluğudur (Hoppe & Fujishiro, 2025; Knappert, Kornau, & Figengül, 2018; Ulusoy, ve diğerleri, 2016). Bu eksiklikler, önerilen kavramsal modelin hem gerekçesini hem de özgün katkısını oluşturmaktadır.

KAVRAMSAL MODEL ÖNERİSİ

Karşılaştırmalı literatür taramasının ortaya koyduğu bulgular, işyerinde ötekileştirmenin ne salt bireysel bir önyargı meselesi ne de tek bir bağlamsal etkenle açıklanabilecek doğrusal bir süreç olduğunu göstermektedir. Bu nedenle çalışma, Sosyal Kimlik Teorisi, Öz-Kategorizasyon Teorisi ve Damgalama Teorisi'ni tek bir yapı altında bütünleştiren dört bileşenli bir kavramsal model önermektedir. Model; bağlamsal etkenler, ötekileştirme süreci, kimlik tepkileri ve bireysel ile örgütsel çıktılar olmak üzere birbirini besleyen dört bileşenden oluşmaktadır. İlk bileşen olan bağlamsal etkenler, süreci çevreleyen ve tetikleyen yapısal koşulları kapsamaktadır. Türkiye bağlamında geçici koruma statüsü ve kayıt dışı istihdamın yarattığı hukuki güvencesizlik (Özel, 2020; Şahin Emir, 2021), Almanya bağlamında ise kültürel ve dinsel kimlik üzerinden kuşaklar boyunca yeniden üretilen kurumsal dışlama (Koopmans, 2016; Kaas & Manger, 2012) bu bileşenin iki farklı görünümünü oluşturmaktadır. Her iki bağlamda ortak biçimde işleyen siyasi kutuplaşma ise ötekileştirmeyi derinleştiren bir çarpan işlevi görmektedir (Korman, Reinwald, Kunze, & Koos, 2025).

Modelin ikinci bileşeni olan ötekileştirme süreci, bağlamsal koşulların bilişsel ve sosyal düzeyde işlediği çekirdek aşamayı temsil etmektedir. Bu aşama, üç teorinin birbirini tamamlayarak açıkladığı üç mekanizmayı içermektedir: dış-grup kategorizasyonu (Tajfel & Turner, 2004), kişisellikten arınma yoluyla bu ayrımın içselleştirilmesi (Turner vd., 1987) ve nihayetinde damganın kurumsal ve örgütsel zeminlere aktarılması (Goffman, 1986; Link & Phelan, 2001). Sürecin çıktısı olan üçüncü bileşen, bireyin ötekileştirmeye verdiği kimlik tepkileridir. Kimlik tehdidi, köken kimliği ile örgütsel özdeşleşme arasındaki gerilim ve bu gerilime karşı geliştirilen uyum stratejileri bu aşamada belirleyici hâle gelmektedir (Ashforth & Mael, 1989; Williams & Liu, 2023). Nitekim karşılaştırmalı bulgular, marjinalleşme stratejisini benimseyen çalışanların her iki bağlamda da en olumsuz sonuçlarla

karşılaştığını göstermektedir (Baban, Ilcan, & Rygiel, 2017). Dördüncü bileşen ise sürecin somut sonuçlarını, yani bireysel düzeyde psikolojik refah kaybı ve toplumsal dışlanma duygusunu, örgütsel düzeyde ise bağlılık ve performans düşüşü, işten ayrılma niyeti ile üretim karşıtı davranışlardaki artışı kapsamaktadır (Gürlek, 2021; Robinson, O'Reilly, & Wang, 2013).



Şekil 1. İşyerinde Ötekileştirmenin Kavramsal Modeli

Önerilen modelin özgün katkısı, bu dört bileşen arasındaki ilişkileri doğrusal değil döngüsel ve etkileşimli bir yapı içinde kavramsallaştırmasıdır. Çıktılar süreci sonlandırmamakta; bireysel ve örgütsel sonuçlar bağlamsal etkenleri yeniden şekillendirerek döngüyü beslemektedir. Örneğin ötekileştirmenin doğurduğu üretim karşıtı davranışlar ya da yüksek işten ayrılma niyeti, göçmen çalışana yönelik kurumsal ve toplumsal algıyı pekiştirerek bir sonraki döngüde ötekileştirme sürecini güçlendirebilmektedir (Gürlek, 2021). Bu döngüsellik, modelin bağlama duyarlı ikinci bir özelliğiyle birleşmektedir: bağlamsal etkenler sürecin yalnızca başlangıcında değil, ötekileştirme sürecinin, kimlik tepkilerinin ve çıktıların her aşamasında düzenleyici bir rol üstlenmektedir. Bu nedenle özünde aynı olan ötekileştirme mekanizmaları, Türkiye ve Almanya bağlamlarında farklı kurumsal zeminler ve kültürel mesafeler altında farklı biçimlerde tezahür etmektedir (Baban, Ilcan, & Rygiel, 2017; Wiedner & Giesecke, 2022).

Bu haliyle model, çalışmanın karşılaştırmalı bulgularını tek bir çatı altında bütünleştirmekte ve iki grubun deneyimini aynı kavramsal çerçeve içinde okunabilir kılmaktadır. Suriyeli çalışanlar için ötekileştirme büyük ölçüde hukuki statünün doğrudan bir ürünüyken, Almanya'daki Türk göçmenler için süreç kültürel-dinsel kimliğin hem görünür hem görünmez bir damgaya dönüştürülmesi yoluyla işlemektedir (Weichselbaumer, 2020). Modelin sunduğu bu bütünleşik ve döngüsel bakış, mevcut yazında sıklıkla vurgulanan üç eksikliğe (karşılaştırmalı çok düzeyli tasarımların yetersizliği, bireysel ve örgütsel sonuçları birlikte ele alan modellerin sınırlılığı ve hem göç alan hem göç veren bağlamları merkeze alan çalışmaların yokluğu) doğrudan yanıt vermeyi amaçlamaktadır. Böylece Şekil 1'de özetlenen model, yalnızca betimleyici bir sınıflandırma değil, gelecekteki ampirik araştırmalar için sınanabilir ilişkiler öneren teorik bir yol haritası niteliği taşımaktadır (Ornek, Weinmann, Waibel, & Radon, 2020; Hoppe & Fujishiro, 2025).

TARTIŞMA VE SONUÇ

Farklılıklar açısından ise tablo daha karmaşık bir görünüm arz etmektedir. Suriyelilerin durumu hukuki güvencesizlik ve yapısal kayıt dışılık tarafından biçimlendirilirken, Türk göçmenlerin deneyimi kültürel-dinsel kimliğin kurumsal ayrımcılığa dönüştüğü köklü ve kuşaklar arası bir süreç olarak kendini göstermektedir. Kolektivist kökenli göçmenlerin bireyci ev sahibi ülkelerde ödüller açısından dezavantajlı konumda bulunduğu anlaşılmaktadır. Bu durumun salt eğitim ya da beceri farklılıklarıyla

değil kültürel uyumsuzluğun örgütsel ödül sistemlerine yansımasıyla da ilişkili olduğu görülmektedir (Baban, Ilcan, & Rygiel, 2017; Baban, Ilcan, & Rygiel, 2017; Wiedner & Giesecke, 2022). Bu bulgu, hem Suriyeli hem de Türk göçmen çalışanlar için geçerliliğini korumakla birlikte Türkiye bağlamında kültürel mesafenin görece kısa olması nedeniyle farklı biçimlerde tezahür etmektedir. Teorik boşluklar açısından ise mevcut literatür üç önemli eksikliği barındırmaktadır (Erol, ve diğerleri, 2023). Bunlar karşılaştırmalı çok düzeyli tasarımların yetersizliği; hem bireysel hem örgütsel sonuçları aynı anda kapsayan bütünleşik modellerin sınırlılığı ve Türkiye gibi hem göçmen gönderen hem de kabul eden bir ülkeyi merkeze alan araştırmaların neredeyse yokluğudur (Gürlek, 2021) (Wiedner & Giesecke, 2022). Bu eksiklikler, bir sonraki bölümde önerilecek kavramsal modelin hem gerekçesini hem de özgün katkısını oluşturmaktadır.

Teorik açıdan değerlendirildiğinde, bu çalışmanın göç ve örgütsel davranış yazınına üç düzeyde katkı sağladığı görülmektedir. Birinci katkı, Sosyal Kimlik Teorisi, Öz-Kategorizasyon Teorisi ve Damgalama Teorisi'nin bütünleşik biçimde ele alınmasıdır (Tajfel & Turner, 2004; Goffman, 1986; Turner, Hogg, Oakes, Reicher, & Wetherell, 1987). Mevcut literatürde söz konusu teoriler büyük ölçüde birbirinden bağımsız kullanılmış, ötekileştirme sürecinin bilişsel, motivasyonel ve kurumsal boyutlarını aynı anda açıklayabilen bütünleşik bir çerçeve geliştirme çabaları oldukça sınırlı kalmıştır. Bu çalışma, üç teorinin birbirini nasıl tamamladığını ve hangi mekanizmalar aracılığıyla etkileşime girdiğini sistematik biçimde ortaya koyarak bu boşluğu doldurmaktadır (Ashforth & Mael, 1989). İkinci katkı, Türkiye'nin hem göç gönderen hem de göçmen kabul eden bir ülke olarak sahip olduğu ikili konumun teorik açıdan işlenmesidir. Bu özgün konum, göç yazınında bugüne kadar yeterince ele alınmamıştır. Türkiye'deki Suriyeliler ile Almanya'daki Türklerin deneyimlerini aynı kavramsal çerçeve içinde karşılaştıran çalışmalar ise neredeyse hiç yapılmamıştır (Badalič, 2023; Hartmann, 2016; Wiedner & Giesecke, 2022).

Öte yandan bu çalışma, bir dizi sınırlılığı da beraberinde taşımaktadır. Her şeyden önce, teorik ve karşılaştırmalı bir literatür taramasına dayanan çalışma, önerilen modelin ampirik olarak sınanmasını kapsamamaktadır. Mevcut literatürün büyük çoğunluğunun nitel yöntemlere dayanmaktadır. Göçmen çalışanları kapsayan nicel ve boylamsal araştırmaların yetersizliği, karşılaştırmalı bulguların genellenebilirliğini kısıtlamaktadır (Knappert, Kornau, & Figengül, 2018). Özellikle ötekileştirme sürecinin zaman içinde nasıl dönüştüğüne ilişkin dinamik örüntülerin anlaşılmasını güçleştirmektedir. Üçüncü sınırlılık, her iki bağlamdaki göçmen nüfusunun kendi içindeki heterojenliğidir (Erol, ve diğerleri, 2023; Mohammed, 2024). Vasıf düzeyi, göç süresi, aile yapısı ve din gibi bireysel düzey değişkenlerin ötekileştirme süreci üzerindeki farklılaştırıcı etkileri, bu çalışmada yeterince derinleştirilemeyen bir boyut olarak kalmaktadır.

Gelecekteki araştırmalar için çeşitli öneriler sunmak mümkündür. Öncelikle, önerilen modelin her iki bağlamda da ampirik olarak test edilmesi; bireysel, örgütsel ve kurumsal düzeyleri aynı anda kapsayan çok düzeyli araştırma tasarımlarının hayata geçirilmesi gerekmektedir. Buna ek olarak, psikolojik güvenlik, kapsayıcı liderlik ve örgütsel çeşitlilik-kapsayıcılık iklimi gibi değişkenlerin modele düzenleyici etkenler olarak eklenmesi, ötekileştirmenin olumsuz çıktılarını hafifletebilecek müdahale noktalarının belirlenmesine önemli katkılar sağlayacaktır. Son olarak, Türkiye ve Almanya'nın yanı sıra üçüncü bağlamları da kapsayan genişletilmiş karşılaştırmalı çalışmalar, modelin evrensellik iddiasını güçlendirecek ve teorik çerçevenin sınırlarını daha net biçimde çizecektir.

Sonuç olarak bu çalışma, işyerinde ötekileştirme olgusunun hem bireysel hem de örgütsel düzeyde derin ve kalıcı izler bırakan bir süreç olduğunu göstermektedir. Bu sürecin anlaşılmasının yalnızca akademik bir mesele olmaktan öte, göçmen istihdamına ilişkin politika ve örgütsel uygulama kararları açısından da kritik bir öneme sahip olduğunu vurgulamaktadır. Türkiye'nin hem göçmen gönderen hem de kabul eden bir ülke olarak bulunduğu ikili konum, bu tartışmayı küresel göç yazınında özgün ve değerli bir konuma taşımaktadır. Önerilen bütünleşik kavramsal modelin, alandaki boşlukları doldurmaya ve gelecekteki ampirik çalışmalara teorik bir yol haritası sunmaya katkı sağlayacağı düşünülmektedir.

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NUMERICAL APPROXIMATION USING A COLLOCATION SCHEME WITH QUINTIC HERMITE BASIS FUNCTIONS

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ABSTRACT
Mathematical modeling of natural processes across engineering and physics relies heavily on ordinary, partial, and more widely fractional differential equations. However, real-world complexity—stemming from non-standard domain geometries and non-linear material behaviors—precludes exact analytical solutions in most practical applications. To bridge this gap, numerical approximation methods are widely employed. Established techniques in the literature include finite difference, variational, differential quadrature, and finite element approaches. This work investigates the approximate solution of a predefined boundary-value problem using the collocation finite element method based on quintic Hermite B-spline basis fucntions. To establish a clear quantitative assessment, a prototype problem possessing an exact analytical solution is utilized. The accuracy of the computational scheme is measured using L_2 and L_∞ error norms. Detailed simulation outputs are provided through comprehensive tables and graphical plots, and the performance of the proposed method is validated against established benchmark studies in the literature.
Keywords: Quintic Hermite B-spline; Collocation method; Shifted Legendre and Chebyshev polynomials Roots, Finite Element Method.

Financial support for this research was provided by Inonu University Scientific Research Projects (Project No. FYL-2026-4682)."

INTRODUCTION
This study employs the collocation Finite Element Method (FEM) based on quintic Hermite B-spline basis functions to solve a prototype problem. The primary objective is to delineate the foundational procedural steps of the collocation finite element procedure, thereby providing a clear computational framework that can be extended by researchers to model various physical phenomena governed by linear and nonlinear Partial Differential Equations (PDEs) and Ordinary Differential Equations (ODEs) or even Fractional Order Differential Equations.
Although the Finite Element Method has been originally introduced by Clough (1960), subsequent technological progress in digital computer science—most notably exponential increases in CPU processing speeds and memory capacities—has driven its widespread adoption in numerical analysis. The core principle underlying the FEM is the transformation of complex, continuous initial- and boundary-value differential problems into solvable systems of algebraic equations. A key advantage of the FEM over alternative numerical approximation techniques lies in its piecewise element-wise representation: by constructing local interpolation functions across each element, the method yields continuous solution values at any arbitrary interior point in addition to discrete nodal values.
Methodologically, the global continuous solution domain is partitioned into subdomains termed elements, interconnected at specific nodes. Rather than attempting a direct global solution across the entire domain simultaneously, element-level algebraic equations are formulated for typical subdomains and subsequently assembled to determine the global numerical solution across the entire domain (Logan, 2007). According to Reddy (1993), the fundamental procedural steps of the finite element methodology can be summarized as follows:

1. Domain Discretization: The spatial domain of the governing differential equation is partitioned into a finite number of non-overlapping subdomains (finite elements).
2. Local Element Formulation: The element-level algebraic equations are derived for a representative typical element using suitable basis functions.

3. Global Assembly: The individual elemental systems are assembled into a global system of equations governing the entire continuous domain.
4. Applying the Boundary Conditions: Both natural and essential boundary conditions specified in the problem formulation are applied to modify the global system matrix.
5. Numerical Solution: An efficient computational solver implemented in a high-level programming language is utilized to solve the constrained algebraic system.
6. Post-Processing and Error Analysis: The resulting numerical solution is post-processed, visualized, and evaluated to assess accuracy and convergence.

LITERATURE SURVEY

This section provides a brief overview of recent developments in finite element collocation methods and the various spline basis functions employed in the literature.

Numerical approximations of non-linear wave equations using spline-based collocation techniques have been widely investigated. For instance, Ganaie and Kukreja (2014) applied a collocation finite element method (FEM) based on cubic Hermite basis functions to solve Burgers' equation. Regarding the Generalized Equal-Width (GEW) wave equation, Karakoç and Zeybek (2016) implemented a Galerkin finite element scheme using classical cubic B-spline bases, while Ganaie et al. (2015) utilized a cubic Hermite collocation framework. In related work on wave models, Yağmurlu and Karakaş (2020) examined trigonometric cubic basis splines for the Equal-Width (EW) equation and introduced a novel Rubin–Graves linearization technique for the modified EW equation.

Higher-order and optimal spline formulations have also been extensively developed for regularized wave and transport models. Shallu and Kukreja (2023) formulated an optimal spline collocation scheme coupled with implicit Crank–Nicolson and explicit SSP-RK43 time integrations for the Generalized Regularized Long-Wave (GRLW) equation. Similarly, Kumari and Kukreja (2023) employed a septic Hermite collocation method combined with Crank–Nicolson and SSP-RK43 algorithms to capture soliton dynamics in the GRLW equation.

For parabolic transport problems, such as 1D heat conduction, Kutluay et al. (2022) initially applied cubic Hermite bases, which was later extended by Kutluay et al. (2024) using higher-order quintic Hermite B-spline collocation. In further recent applications, Kutluay et al. (2024) proposed a new way for simulating the MEW equation using cubic Hermite B-splines, while Kumar (2024) demonstrated advanced applications of the cubic Hermite collocation technique.

COLLOCATION METHOD

This section outlines the mathematical framework of the numerical methodology employed in this study. To formulate the proposed scheme, consider the general differential operator equation defined over the domain Ω:

$A\mathrm{u} = f.$ **(1)**

Where A denotes either a non-linear or linear differential operator, u represents the unknown dependent variable, and f is a prescribed source function. The numerical solution U_M, formulated to approximate the exact analytical solution u, is expressed as follows:

$$U_M = \sum_{j=1}^{M} a_j \omega_j + \omega_0$$

Here, ω_j's denote the predefined approximation (basis) functions, and a_j's represent the unknown expansion coefficients determined by applying the proposed numerical scheme together with the prescribed boundary and initial conditions. Substituting the approximate solution U_M for the analytical solution u into Equation **(1)** yields the following relation:

$A(U_M) \approx f.$

The term appearing in the last equation

$A(U_M) - f$

is widely recognized as the residual of the approximate solution and it has been given in the following form (Reddy, 1993)

$$R(x, y, a_j) = A(U_M) - f = A(\sum_{j=1}^{M} a_j \omega_j + \omega_0) - f \neq 0.$$

For the implementation of the Finite Element Method (FEM), the governing differential equations are converted into the following weighted residual integral form:

$$\int_{\Omega}^{0} \omega_l(x,y) R\big(x,y,a_j\big) d\boldsymbol{x} = 0 \quad (\mathbf{2})$$

is taken into consideration. Here, the solution domain Ω of the main equation may represent a multi-dimensional region, and ω_l (for $l = 1(1)N$) denotes the weighting (test) functions, which may either coincide with or differ from the basis functions ω_j. The specific choice of weighting functions ω_l categorizes the underlying finite element formulation into variants such as Least Square, Petrov–Galerkin, Galerkin, collocation or subdomain methods. In this study, the collocation approach is adopted, wherein the governing residual is required to vanish identically at designated collocation nodes. $\boldsymbol{x}_i = (x_{i1}, x_{i2}, \ldots)(for\ i = 1(1)N)$.

Specifically, adopting the point collocation method entails selecting the weighting functions ω_l's in Equation **(2)** as Dirac delta functions, $\delta(\boldsymbol{x} - \boldsymbol{x_i})$, which reduces Equation **(2)** to the following form:

$\int_{\Omega}^{0} \delta(\boldsymbol{x} - \boldsymbol{x_i})\, R(\boldsymbol{x}, a_j) d\boldsymbol{x} = 0 \quad (\mathbf{3})$

To facilitate readability, Equation **(3)** is reformulated as follows:

$\int_{\Omega}^{0} \delta(\boldsymbol{x} - \boldsymbol{x_i})\, dx = 1$ **x=$\boldsymbol{x_i}$,**

$\int_{\Omega}^{0} \delta(\boldsymbol{x} - \boldsymbol{x_i})\, dx = 0$ $\boldsymbol{x \neq x_i}$

The selection and distribution of collocation points play a pivotal role in ensuring the well-posedness and convergence rate of the resulting linear system (Reddy, 1993). In the implementation of the present collocation scheme, the formulation utilizes both global and local coordinate systems. The physical domain is mapped from global coordinates to a normalized local coordinate space, wherein finite elements of either uniform or non-uniform mesh sizes h are established. Local element equations are derived within this coordinate frame, after which global boundary conditions are applied to recover the complete field solution across the physical domain.

A key distinguishing feature of the present work can be found in the evaluation strategy associated by Hermite basis functions. While conventional formulations in the literature predominantly employ classical, trigonometric, or exponential splines evaluated directly at the primary grid nodes, the present Hermite-based scheme utilizes interior collocation points situated between adjacent nodes. To ensure consistency and enable direct quantitative comparison with benchmark studies reported in the literature, the computed numerical fields are evaluated at the standard grid nodes. The resulting tabular data and graphical illustrations effectively highlight the physical characteristics and accuracy of the proposed model.

THE DERIVATION OF THE HERMITE BASES

Quintic Hermite basis functions serve as the primary approximation functions in the present study. A concise derivation of these basis functions is provided herein. As is standard practice, upon establishing the order of the governing differential equation, trial polynomials of matching or higher degree are chosen to initiate the approximation process.

To establish the mathematical formulation, a polynomial defined as follows is introduced:

$$P(x) = \boldsymbol{a}x^5 + \boldsymbol{b}x^4 + \boldsymbol{c}x^3 + \boldsymbol{d}x^2 + \boldsymbol{e}x + \boldsymbol{f} \quad (\mathbf{4})$$

defined on the unit interval [0,1] is selected. As evident, the expression depends on six unknown coefficients $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}, \boldsymbol{d}, \boldsymbol{e}$, f. The goal is to reformulate these parameters in terms of the boundary values of the polynomial and its corresponding first- and second-order derivatives at x in [0,1]
$P(0), P(1), P'(0), P'(1), P''(0), P''(1)$.

Alternatively, formulating $P(x)$ using its boundary values and corresponding derivative constraints at the endpoints $x = 0$ and $x = 1$ yields the following expressions for the unknown coefficients:

$$\boldsymbol{a} = -\mathbf{6}P(0) - 3P'(0) + 6\,P(1) - 3P'(1) - \frac{P''(0) + P''(1)}{2},$$

$$\boldsymbol{b} = \mathbf{15}P(0) - 8P'(0) - 15\,P(1) + 7P'(1) - \frac{3P''(0) - 2P''(1)}{2},$$

$$\boldsymbol{c} = -\mathbf{10}P(0) + 10P'(0) + 10\,P(1) - 4P'(1) + \frac{P''(1) - 2 - P''(0)}{2},$$

$$\mathbf{d} = \frac{P''(0)}{2}$$

$$\mathbf{e} = P'(0)$$

$$\mathbf{f} = P(0)$$

Given that these conditions must be satisfied, performing algebraic substitution into Equation **(4)** leads directly to the following equality:

$P(x) = P(0)[-6x^5 + 15x^4 - 10x^3 + 1] + P'(0)[-3x^5 + 8x^4 - 6x^3 + x] + P''(0)[-x^5/2 + 3x^4/2 - 3x^3/2 + x^2/2] + P''(1)[1/2x^5 - x^4 + 1/2x^3] + P(1)[6x^5 - 15x^4 + 10x^3] + P'(1)[-3x^5 + 7x^4 - 4x^3]$

Here, the bracketed terms denote the set of quintic Hermite shape functions, H_i (for i = 1, 2, …, 6). For additional insights into the construction and properties of this basis, see Kutluay et al. (2024) and the references cited therein. Figures 1 and 2 present graphical visualizations of these functions from three perspective views and over a single finite element, respectively.

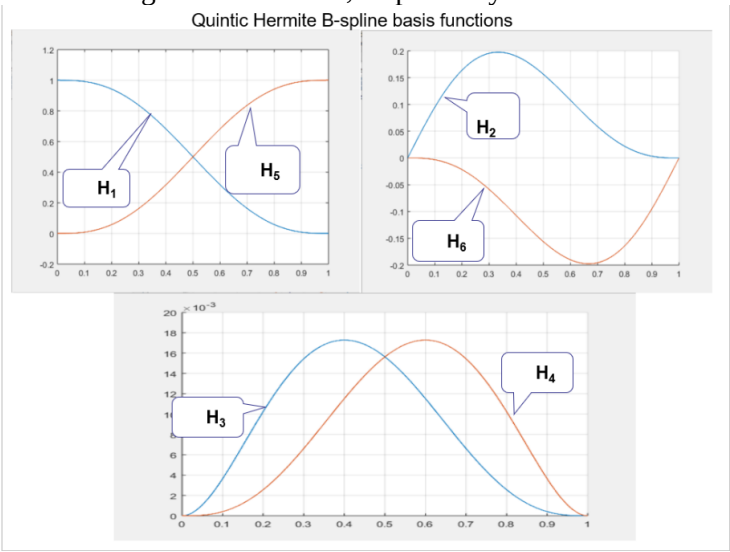


Figure 6 Graphical representation of the six quintic Hermite basis functions on three distinct perspectives.

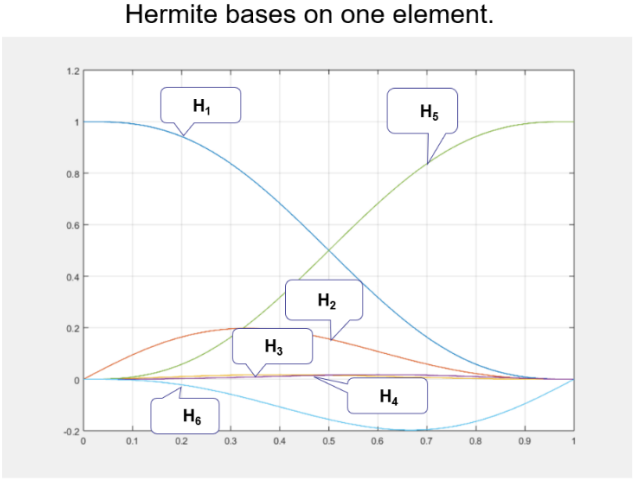


Figure 7 Profiles of the six quintic Hermite shape functions defined on an individual finite element.

SHIFTED LEGENDRE VE CHEBYSHEV POLYNOMIAL ROOTS

A key advantage of integrating Hermite basis functions into the collocation finite element framework lies in performing calculations at interior collocation nodes instead of primary grid boundaries. In this study, the implementation of quintic Hermite basis functions necessitates four interior collocation points per spatial element. To maximize numerical precision, these points are selected as the shifted roots (quadrature nodes) of Legendre and Chebyshev polynomials. Specifically, the shifted Legendre roots are given by:

$\xi_1^L = 0.069431844202974, \qquad \xi_2^L = 0.330009478207572$

$\xi_3^L = 0.669990521792428, \qquad \xi_4^L = 0.930568155797026$

and shifted Chebyshev roots

$\xi_1^C = 0.038060233744357, \qquad \xi_2^C = 0.308658283817455$

$\xi_3^C = 0.691341716182545, \qquad \xi_4^C = 0.961939766255643.$

are utilized in the solution process (Kutluay et al., 2024). In this study, computational results corresponding to both sets of quadrature nodes are reported in the tables using the designations L (for shifted Legendre roots) and C (for shifted Chebyshev roots). The primary rationale for selecting these specific interior collocation points stems from their well-documented capability in the literature to minimize numerical error across simulations. Furthermore, as an alternative to classical orthogonal polynomial roots, a set of novel shifted roots proposed in this work is evaluated and designated as (Special) in the comparative tables below:

$\xi_1 = \frac{1}{5}, \qquad \xi_2 = \frac{2}{5}, \qquad \xi_3 = \frac{3}{5}, \qquad \xi_4 = \frac{4}{5}.$

MODEL PROBLEM

In accordance with the aforementioned scope, this investigation focuses on applying the proposed quintic Hermite collocation method to a characteristic prototype boundary-value problem. To achieve this objective, the following benchmark model equation is examined:

$$\frac{d^2U}{dx^2} + U = x^2 e^{-x}$$

on the following solution domain

$$0 < x < 10$$

by the following conditions given at the boundaries of the problem

$U(0) = 0,\ U(10) = 0.$

For validation purposes, the exact solution to this problem is available and expressed as follows:

$$U(x) = \frac{1}{2}e^{-x}\left[1 + 2x + x^2 - e^x \cos x - 2e^x\left\{-\frac{\cot 10}{2} + \frac{121 \csc 10}{2e^{10}}\right\}\sin x\right]$$

Having established the theoretical framework, the quintic Hermite collocation finite element method is now applied to compute numerical solutions. The performance and accuracy of the method are subsequently illustrated through detailed tabular and graphical representations. To achieve this aim, the following form of approximation

$$U_M = \sum_{j=1}^{M+2} a_{j+4k-4}\mathrm{H}_{ji}$$

is utilized in place of the analytical solution. The unknown coefficients to be determined by the proposed numerical scheme and the imposed boundary conditions are denoted by a_{j+4k-4}. Here, k represents the element number, (i) denotes the index of the interior collocation point, and $\mathrm{H}_{ji} = \mathrm{H}_j(\xi_i)$ corresponds to the quintic Hermite basis functions. In accordance with the formulation of the finite element method (FEM), the following transformation from the physical coordinate to the local coordinate is introduced on the k-th element:

$$\xi = \frac{x - x_k}{h}$$

the global closed internal $[x_k,\ x_{k+1}]$ is converted to into closed unit interval $[0,1]$ in the local coordinate system. In terms of this newly obtained local coordinate variable ξ, the quintic Hermite basis functions

$$\mathrm{H}_1(\xi) = -6\xi^5 + 15\xi^4 - 10\xi^3 + 1, \qquad \mathrm{H}_2(\xi) = (-3\xi^5 + 8\xi^4 - 6\xi^3 + \xi)h$$
$$\mathrm{H}_3(\xi) = (-0.5\xi^5 + 1.5\xi^4 - 1.5\xi^3 + 0.5\xi^2)h^2, \quad \mathrm{H}_4(\xi) = (0.5\xi^5 - \xi^4 + 0.5\xi^3)h^2$$
$$\mathrm{H}_5(\xi) = 6\xi^5 - 15\xi^4 + 10\xi^3, \qquad \mathrm{H}_6(\xi) = (-3\xi^5 + 7\xi^4 - 4\xi^3)h$$

and their second order derivatives

$$\mathrm{H''}_1(\xi) = -60\xi + 180\xi^2 - 120\xi^3 \qquad \mathrm{H''}_2(\xi) = (-36\xi + 96\xi^2 - 60\xi^3)h$$
$$\mathrm{H''}_3(\xi) = (1 - 9\xi + 18\xi^2 - 10\xi^3)(h^2) \qquad \mathrm{H''}_4(\xi) = (3\xi - 12\xi^2 + 10\xi^3)(h^2)$$
$$\mathrm{H''}_5(\xi) = 60\xi - 180\xi^2 + 120\xi^3 \qquad \mathrm{H''}_6(\xi) = (-24\xi + 84\xi^2 - 60\xi^3)h$$

are reformulated as outlined above. The discrete field values U_i and their corresponding second-order derivatives U''_i, evaluated at the designated interior collocation points, are expressed as follows:

$$U_i = \mathrm{a}_{4k-3}H_{1i} + \mathrm{a}_{4k-2}H_{2i} + \mathrm{a}_{4k-1}H_{3i} + \mathrm{a}_{4k}H_{4i} + \mathrm{a}_{4k+1}H_{5i} + \mathrm{a}_{4k+2}H_{6i}$$

$$h^2U''_i = \mathrm{a}_{4k-3}H''_{1i} + \mathrm{a}_{4k-2}H''_{2i} + \mathrm{a}_{4k-1}H''_{3i} + \mathrm{a}_{4k}H''_{4i} + \mathrm{a}_{4k+1}H''_{5i} + \mathrm{a}_{4k+2}H''_{6i}.$$

Substituting these expressions into the governing equation and collecting the resulting terms yields the following system of linear algebraic equations:

$$[\mathrm{a}_{4k-3}H''_{1i} + \mathrm{a}_{4k-2}H''_{2i} + \mathrm{a}_{4k-1}H''_{3i} + \mathrm{a}_{4k}H''_{4i} + \mathrm{a}_{4k+1}H''_{5i} + \mathrm{a}_{4k+2}H''_{6i}]/h^2 +$$
$$[\mathrm{a}_{4k-3}H_{1i} + \mathrm{a}_{4k-2}H_{2i} + \mathrm{a}_{4k-1}H_{3i} + \mathrm{a}_{4k}H_{4i} + \mathrm{a}_{4k+1}H_{5i} + \mathrm{a}_{4k+2}H_{6i}] + (\mathrm{h}\xi + x_k) = 0.$$

Upon enforcing the specified boundary conditions on the discretized system, a fully determined global matrix equation is established. Applying these boundary conditions directly results in:

$$\mathrm{a}_1 = 0 \ \ and \ \mathrm{a}_{4M+1} = 0.$$

After eliminating the unknowns from the original system of equations, the resulting system can be expressed in the following form:

$$La = R$$

In this matrix formulation, L and R represent coefficient arrays of dimensions $(4\mathrm{M} \times 4\mathrm{M})$ and $(4\mathrm{M} \times 1)$, respectively. With the general numerical scheme fully established, computational simulations are executed for various numbers of elements M using a computational algorithm implemented in MATLAB (R2021a). To evaluate the precision, convergence, and computational efficiency of the proposed method, standard L_2 and L_∞ error norms are defined as follows:

$$L_2 = \left(h\sum_{i=1}^{M} |U_i - (U_M)_i|^2\right)^{1/2}$$

$$L_\infty = \underbrace{max}_{1\le i\le M} |U_i - (U_M)_i|.$$

Following the formulation of the numerical scheme, the computational code was executed across various partition numbers “M”. The resulting simulation outcomes are presented in Tables I, II, and III.

An examination of the L_2 and L_∞ error norms across increasing mesh subdivisions M in Table I indicates that shifted Legendre quadrature roots yield superior accuracy compared to shifted Chebyshev roots up to a threshold value of M. Beyond this critical discretization parameter, both error norms exhibit a gradual increase. This inflection suggests that finer spatial mesh refinements introduce cumulative floating-point round-off errors that eventually outweigh discretization improvements, underscoring the necessity of determining an optimal element resolution.

An analysis of Tables I and II reveals distinct computational characteristics depending on the choice of inner collocation points. When employing shifted Legendre roots, the formulation exhibits rapid initial convergence, yielding significantly reduced error norms at lower partition numbers “M”. However, beyond a critical element threshold, cumulative floating-point and round-off errors induce numerical degradation, leading to a progressive increase in error norms. Conversely, schemes utilizing shifted Chebyshev roots yield slightly higher initial error norms at smaller partition sizes; nevertheless, this choice demonstrates superior numerical stability and continued accuracy enhancement at higher spatial discretizations “M”, effectively mitigating round-off error accumulation.

Table 1 The corresponding error norms L_2 and L_∞ for different values of M are reported below.

	L_2		L_∞	
M	L	C	L	C
2	0.1940	0.7222	0.0539	0.1897
4	0.0013	0.0167	4.0832e-04	0.0050
8	2.5118e-05	8.4498e-04	1.4993e-05	2.2586e-04
16	4.5132e-07	5.2841e-05	3.5029e-07	1.4846e-05
32	7.3393e-09	3.3515e-06	6.6597e-09	9.4910e-07
64	1.1585e-10	2.1044e-07	1.1467e-10	5.9735e-08
128	1.8061e-12	1.3170e-08	1.8801e-12	3.7459e-09
256	5.5318e-13	8.1930e-10	1.5987e-13	2.3324e-10

Table 2 The L_2 and L_∞ error norms computed for different spatial element sizes are presented below.

	L_2		L_∞	
M	L	C	L	C
10	7.0150e-06	3.4248e-04	4.6247e-06	9.3675e-05
50	5.0847e-10	5.6433e-07	4.9081e-10	1.6035e-07
100	7.9832e-12	3.5340e-08	8.1592e-12	1.0048e-08
150	9.4390e-13	6.9831e-09	7.3194e-13	1.9859e-09
200	5.9170e-13	2.2111e-09	1.9584e-13	6.2893e-10

Table III presents a comparative evaluation of the numerical results obtained using shifted Legendre, shifted Chebyshev, and the proposed special interior collocation roots. It is evident from the data that the shifted Legendre formulation yields significantly superior accuracy compared to both alternative root selections up to a specific mesh refinement parameter M.

Table 3 The error norms L_2 and L_∞ obtained for different values of (M) using the three types of interior collocation points are presented.

	L_2			L_∞		
M	L	C	Special	L	C	Special
25	3.1999e-08	8.9639e-06	8.6553e-05	2.7732e-08	2.5389e-06	2.4579e-05
50	5.0847e-10	5.6433e-07	5.4801e-06	4.9081e-10	1.6035e-07	1.5590e-06
100	7.9832e-12	3.5340e-08	3.4364e-07	8.1592e-12	1.0048e-08	9.7760e-08
200	5.9170e-13	2.2111e-09	2.1495e-08	1.9584e-13	6.2893e-10	6.1148e-09

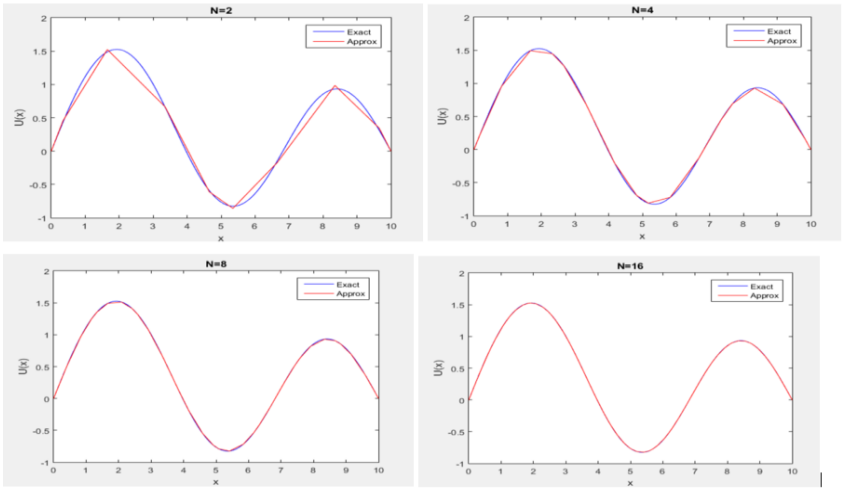


Figure 3 Graphical representation of both the analytical and approximate solutions for M=2,4,8 and 16.

CONCLUSION AND DISCUSSION

This study investigates the application of the collocation Finite Element Method (FEM) utilizing quintic Hermite B-spline basis functions to solve a representative model problem. To establish a rigorous analytical framework, several foundational mathematical concepts and procedural steps are detailed: the mathematical structure and properties of quintic Hermite basis functions, the formulation of the collocation FEM, the spectral properties of shifted Legendre and Chebyshev roots for inner collocation points, a concise literature review, and the numerical implementation of the proposed scheme.

Comparative results presented in tabular and graphical formats demonstrate that quintic Hermite basis functions yield superior approximation accuracy compared to conventional polynomial and trigonometric basis sets. Owing to these enhanced convergence and accuracy characteristics, Hermite basis functions have increasingly gained prominence in computational modeling. Given its strong numerical accuracy, the presented quintic Hermite collocation framework provides a robust computational approach for obtaining approximate solutions to a wide range of linear and nonlinear initial- and boundary-value problems across scientific disciplines.

FINANCIAL DISCLOSURE

Financial support for this research was provided by the Scientific Research Projects Unit of İnönü University under Project Number FYL-2026-4682.

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PALEOSEISMOLOGICAL EVIDENCE FOR HOLOCENE SURFACE RUPTURING ALONG THE KAVAKBAŞI FAULT ZONE

KAVAKBAŞI FAY ZONU'NDA HOLOSEN DÖNEMİ YÜZEY FAYLANMASININ PALEOSİSMOLOJİK KANITLARI

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Abstract
The NW-trending, right-lateral strike-slip Kavakbaşı Fault Zone (KFZ) is one of the major tectonic structures in southeastern Türkiye, extending across the provinces of Bingöl, Muş, and Bitlis. To the west, the KFZ terminates against the East Anatolian Fault and forms an approximately 4-km-wide deformation zone comprising several short, subparallel fault strands. From the vicinity of Yenibaşak (Solhan, Bingöl), the fault zone extends predominantly linearly eastward, displaying minor geometric stepovers near İnandık, Kayalısu, Üçevler, Ekindüzü, and Beşevler. Although no destructive historical earthquakes have been documented in the region, earthquakes with magnitudes of $2 \leq M \leq 4$ have been recorded during the instrumental period. To investigate the past seismic activity of the KFZ, paleoseismological trenches were excavated approximately perpendicular to the fault trace at three locations: Yenibaşak, Üçevler, and Bozburun. The trench walls were cleaned, gridded, photographed, and logged in detail, and radiocarbon samples were collected to constrain the ages of the identified event horizons. Integrated evaluation of stratigraphic and structural observations together with radiocarbon dating results indicates that at least one surface-rupturing earthquake occurred along the Kavakbaşı Fault Zone during the Holocene. This finding provides evidence for Holocene activity of the KFZ and contributes to the assessment of the seismic hazard associated with the fault zone.
This study was supported within the scope of subproject No. 128G019 of the project entitled "Determination of the Paleoseismological Characteristics of Active Faults in Türkiye," conducted under the TÜBİTAK Public Research Support Group (KAMAG) 1007 Program.
Keywords: Kavakbaşı Fault Zone, Paleoseismology, Surface Rupture

Özet
Sağ yanal doğrultu atımlı ve KB uzanımlı Kavakbaşı Fay Zonu (KFZ), Bingöl, Muş ve Bitlis illeri sınırlarından geçen, Türkiye'nin güneydoğusundaki önemli tektonik yapılardan biridir. Batıda Doğu Anadolu Fayı tarafından sonlandırılan KFZ, bu kesimde yaklaşık 4 km genişliğinde bir deformasyon zonu içerisinde birbirine yaklaşık paralel kısa fay kollarından oluşmaktadır. Yenibaşak (Bingöl/Solhan) yakınlarından doğuya doğru çoğunlukla doğrusal bir uzanım gösteren fay zonu; İnandık, Kayalısu, Üçevler, Ekindüzü ve Beşevler çevresinde küçük geometrik sıçramalar sergilemektedir. Bölgede

tarihsel döneme ait yıkıcı bir deprem kaydı bulunmamakla birlikte, aletsel dönemde $2 \leq M \leq 4$ büyüklüğünde depremler kaydedilmiştir. KFZ'nin geçmiş deprem aktivitesinin araştırılması amacıyla Yenibaşak, Üçevler ve Bozburun olmak üzere üç farklı lokasyonda fay izine yaklaşık dik paleosismolojik hendekler açılmıştır. Hendek duvarlarında temizlik, karelajlama, fotoğraflama ve ayrıntılı loglama çalışmaları gerçekleştirilmiş; belirlenen olay seviyelerinin yaşlandırılması amacıyla radyokarbon örnekleri alınmıştır. Stratigrafik ve yapısal gözlemler ile radyokarbon tarihlendirme sonuçlarının birlikte değerlendirilmesi, Kavakbaşı Fay Zonu'nda Holosen döneminde en az bir yüzey faylanması oluşturan büyüklükte bir depremin meydana geldiğini göstermektedir. Bu bulgu, KFZ'nin Holosen aktivitesini ortaya koyması ve fay zonunun deprem tehlikesinin değerlendirilmesine katkı sağlaması açısından önem taşımaktadır.

Bu çalışma, TÜBİTAK Kamu Araştırmaları Destek Grubu (KAMAG) 1007 Programı kapsamında yürütülen "Türkiye Diri Faylarının Paleosismolojik Özelliklerinin Belirlenmesi" başlıklı projenin 128G019 numaralı alt projesi kapsamında desteklenmektedir.

Anahtar kelimeler: Kavakbaşı Fay Zonu, Paleosismoloji, Yüzey Faylanması

PROTOCOL PERFORMANCE ANALYSIS OF ADAPTIVE DUTY-CYCLING MECHANISMS IN WIRELESS SENSOR NETWORKS

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ABSTRACT

In wireless sensor networks (WSNs), there is a persistent trade-off between energy conservation and network performance in terms of latency and packet delivery. Duty cycling, which schedules the sleep and wake states of the radio, is among the most effective techniques for extending network lifetime, yet the relative merits of static and adaptive approaches remain insufficiently compared under equivalent conditions. This paper presents a controlled, large-scale simulation study comparing four representative duty-cycling protocols: Static Duty Cycling (SDC), Traffic-Aware Adaptive Duty Cycling (TADC), Receiver-Initiated Duty Cycling (RIDC), and Prediction-Based Adaptive Duty Cycling (PBDC). Using NS-3 with the IEEE 802.15.4 physical layer, more than 5,000 simulation runs were executed across network sizes of 50 to 500 nodes, two topologies (random and grid), and three traffic patterns (constant bit rate, event-driven, and periodic). Results show that PBDC achieves up to 32% greater energy savings than SDC and extends the time to first node failure by 62%, while RIDC reduces average end-to-end latency by 49% and achieves the highest packet delivery ratio (91.2%) under high traffic. TADC offers a balanced compromise, improving both energy efficiency (7-15%) and latency (30-40%) relative to SDC. No single protocol dominates across all operating regimes; protocol choice should therefore be guided by application-specific traffic and latency requirements. A protocol-selection framework is proposed to support this decision for WSN designers.

Keywords: Wireless Sensor Networks, Duty Cycling, Energy Efficiency, Medium Access Control, Network Lifetime

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are currently used in various applications such as environmental monitoring, precision agriculture, factory automation and smart city. Energy conservation is one of the major design concerns, since the radio subsystem consumes 50-80% of the total energy consumed by the sensor nodes. The best way to minimize this cost is to duty cycle the radio between listening and sleep modes, as up to 60% of radio energy can be lost in an always-on radio network. Duty cycling however presents a fundamental trade-off: decreasing the active time is an effective way to save energy but it introduces latency and can cause poor packet delivery, especially in multi-hop topologies (Anastasi et al., 2009). The early duty-cycling schedules were based on fixed sleep/wake cycles. In synchronous solutions, like S-MAC (Ye et al., 2002), the windows do not listen while they are idle and this results in an overhead in communication. T-MAC (Van Dam & Langendoen, 2003), on the other hand, adapts the active window to traffic it hears. Overhead is avoided in asynchronous, low power-listening protocols like B-MAC (Polastre et al., 2004) and X-MAC (Buettner et al., 2006), but moved to the preamble. In contrast, receiver-initiated designs (Sun et al., 2008) broadcast a wake beacon from the receiver and respond opportunistically to it. The study in the literature has mostly considered traffic-aware schemes (Alhammad et al., 2026) and prediction-based schemes individually, against static baselines, and not against each other in similar, large-scale environments (Langendoen & Meier, 2010).

Duty-cycling strategies can be categorized in three mutually orthogonal dimensions: synchronization (synchronous vs. asynchronous), triggering the communication (initiator: sender vs. receiver), and adaptability (static vs. dynamic). WiseMAC (El-Hoiydi & Decotignie, 2007) and ContikiMAC (Dunkels, 2011) refine the asynchronous, low-power-listening idea by having each node learn its neighbours' wake-up schedules, shortening the preamble needed to reach them. The IEEE 802.15.4 standard itself defines an optional beacon-enabled superframe for duty cycling, but its synchronous structure is often too rigid for highly dynamic traffic, which motivates the adaptive mechanisms studied here. Performance evaluation in this area has relied mainly on analytical modelling, simulation, or small testbeds (Wang et al., 2006; Doudou et al., 2012); analytical models offer insight but rely on simplifying assumptions, while most simulation studies compare at most two protocols at a modest scale, leaving comparative, large-scale evidence scarce (Langendoen & Meier, 2010; EkbataniFard & Monsefi, 2012). This paper addresses that gap through a systematic, simulation-based comparison of four representative protocols SDC, TADC, RIDC, and PBDC across a wide range of network sizes, topologies, and traffic

conditions, using NS-3 with the IEEE 802.15.4 physical layer. The contributions of this study are: (1) a quantitative characterization of the energy-latency trade-off for each adaptation paradigm; (2) a network-lifetime analysis accounting for the time to first node failure under heterogeneous traffic; (3) a scalability study up to 500 nodes; and (4) a practical protocol-selection framework linking application requirements to protocol choice. Section 2 describes the four protocols, the theoretical energy/latency models, and the simulation methodology; Section 3 presents the results together with a discussion of trade-offs, limitations, and comparison with prior work; Section 4 concludes the paper and outlines recommendations for future research.

2. MATERIALS AND METHODS

2.1 Duty-Cycling Protocols Under Study

Static Duty Cycling (SDC) employs a fixed cycle period *T* and a fixed active portion α (which is not related to network conditions). No control messages and has minimal computational overhead, but slow response to traffic variation leads to buffer overflow under "bursty" load, and loss of energy under "sparse" load.

Traffic-Aware Adaptive Duty Cycling (TADC) checks the queue length Q locally and changes α within the limits (5-30%) whenever the value of Q is below or above the lower/upper thresholds (2 and 5 packets in this study, respectively); α is re-evaluated every T_{adapt} = 5 s. The adaptation logic is light weight, using an exponentially weighted queue average and a threshold comparison, which moves the energy distribution load away from idle listening towards a small additional computation load once a week, and is able to shift the load from a large delay in reactivation of the load to a small periodicity in computation cost, for a cost of a slight increase in complexity.

In Receiver-Initiated Duty Cycling (RIDC), it completely eliminates the fixed active/sleep schedule: when a receiver wakes up it broadcasts a short beacon (10 bytes, every 500 ms in this study) and any node with data queued will broadcast as soon as it detects the beacon, backing off and retrying upon collision. In particular, the periodic beacon is well suited to many-to-one (sensor-to-sink) traffic and the energy shift is from the transmitter to the receiver, which must listen for every beacon; under light load, the periodic beacon consumes 12-18% of the total energy.

Prediction-Based Adaptive Duty Cycling (PBDC) forecasts the next packet arrival using an exponentially weighted moving average (EWMA, γ = 0.4) of the last $N_{history}$ = 10 inter-arrival timestamps, and schedules a brief wake window ($T_{listen\_predict}$) that opens a safety margin (T_{wakeup_margin}) before the predicted arrival time. Between forecasted events, the node falls back to a low baseline duty cycle (α_base = 5%) to remain reachable and robust to misprediction. This design allows very aggressive sleeping when traffic is regular, at the cost of a bimodal latency profile and additional energy spent on false wake-ups when the prediction is wrong.

For a single hop under ideal channel conditions, the expected per-node energy of the four schemes follows $E_{SDC} = \alpha \cdot P_{active} \cdot T + (1-\alpha) \cdot P_{sleep} \cdot T$; E_{TADC} replaces the fixed α with a traffic-dependent α(Q) plus a negligible adaptation cost E_{adapt}; $E_{RIDC} = (T/T_{beacon}) \cdot E_{beacon} + R \cdot (E_{tx} + E_{rx})$, where R is the number of packets handled; and $E_{PBDC} = R \cdot E_{rx} + (T - R \cdot T_{rx}) \cdot P_{sleep} + E_{predict} + N_{false} \cdot E_{false}$, where E_{false} is the extra cost of an unnecessary wake triggered by a missed prediction. The corresponding expected per-hop latencies are T/2 for SDC, T(Q)/2 for TADC, $T_{beacon}/2 + T_{tx}$ for RIDC, and either T_{tx} (correctly predicted) or $T/2 + T_{tx}$ (unpredicted) for PBDC. These closed-form expressions assume perfect synchronization and single-hop delivery; Table 1 summarizes the key assumption and the corresponding limitation of each model, which multi-hop accumulation, collisions, and channel errors expose only through simulation (Section 3).

Table 1. Theoretical model assumptions and limitations.

Model	Key assumption	Not captured
SDC	Perfect synchronization, no collisions	Multi-hop accumulation, queuing delay
TADC	Linear relationship between queue and duty cycle	Adaptation lag, threshold sensitivity
RIDC	No beacon collisions, immediate sender response	Beacon overhead, hidden-terminal effects
PBDC	Stationary traffic, accurate EWMA	Misprediction cost, pattern changes

2.2 Simulation Environment and Parameters

All four protocols were implemented from scratch in NS-3 (v3.36) using its IEEE 802.15.4 physical/MAC models (2.4 GHz, 250 kbps, 0 dBm transmit power, -85 dBm receiver sensitivity, log-distance path loss with exponent 2.5). The radio energy model follows the CC2420 transceiver used on TelosB/MICAz platforms: 52.2 mW transmit, 59.1 mW receive and idle-listening, and 0.06 mW sleep power, with a 1 ms / 0.2 mJ sleep-to-active transition cost. Table 1 summarizes the protocol-specific parameters.

Table 2. Protocol-specific simulation parameters.

Parameter	SDC	TADC	RIDC	PBDC
Base cycle T	1000 ms	500-2000 ms	N/A	1000 ms
Duty cycle α	10%	5-30%	N/A	5% (baseline)
Beacon period	N/A	N/A	500 ms	N/A
Adaptation interval	N/A	5 s	N/A	per packet
EWMA weight γ	N/A	0.3	N/A	0.4

Two topologies were tested. The random deployment scattered 50, 100, 200, or 500 nodes uniformly over a square area scaled to preserve an average node degree of 6-8 (e.g., 224 m × 224 m for 500 nodes), with the sink placed centrally. The grid deployment placed 49 (7×7) to 400 (20×20) nodes on a regular lattice with 15 m spacing and the sink at a corner, to emulate structured environments such as buildings or agricultural fields. Three traffic patterns were used: (1) constant bit rate (CBR), with each node sending 50-byte packets at λ = 0.1, 0.5, 1.0, or 2.0 packets/s, start times jittered over 10 s to avoid synchronization artefacts; (2) event-driven traffic, generated by a Poisson process (rate 0.1 or 0.5 events/s) in which all nodes within a 30 m radius of the event burst 10 packets at 100 ms intervals on top of a 0.01 packets/s background rate; and (3) periodic monitoring, in which all nodes report synchronously every 30, 60, or 120 s to emulate a worst-case, correlated reporting load.

A full-factorial design (4 protocols × 2 topologies × 4 network sizes × 3 traffic patterns, each with 30 random-seed replications of up to 3,600 simulated seconds, the first 100 s discarded to remove start-up bias) produced more than 5,000 individual simulation runs. A simplified geographic-forwarding routing layer, each node forwards to its neighbor closest to the sink was used so that observed differences could be attributed to the MAC-layer duty-cycling mechanism rather than to routing effects. Energy (per-node and network-wide, broken down by TX/RX/idle-listen/sleep components), end-to-end latency (mean, median, 95th percentile, per-hop), packet delivery ratio (overall and by loss cause: buffer overflow, collision, channel error, timeout), network lifetime (time to first node death, 10% and 50% node death, residual-energy distribution), and control overhead (beacon and adaptation-computation energy) were recorded for every run. Nodes were modelled with a 50-packet buffer and a 5,000 mAh battery for lifetime extrapolation. Statistical significance was assessed with one-way ANOVA (α = 0.05) followed by Tukey HSD post-hoc tests, after verifying normality (Shapiro-Wilk) and homogeneity of variance (Levene's test); 95% confidence intervals are reported where applicable.

3. RESULTS AND DISCUSSION

3.1 Energy Consumption

Under low traffic (λ = 0.1 packets/s, 100-node random topology), PBDC consumed the least energy per node (847 ± 52 mJ), 32% below SDC (1,247 ± 43 mJ); TADC improved on SDC by 7.3% (1,156 ± 38 mJ) by lowering its average duty cycle to α_avg = 6.8% during sparse traffic, while RIDC consumed the most (1,523 ± 67 mJ) owing to its periodic beacon (ANOVA: $F(3,116) = 47.2$, $p < 0.001$; post-hoc ordering PBDC < TADC < SDC < RIDC, all $p < 0.01$ except SDC-TADC at 50 nodes). Per-node energy scaled sub-linearly with network size for all protocols (exponent 0.73-0.81), reflecting a growing but bounded relay burden in larger networks.

This ordering reverses under high traffic (λ = 2.0 packets/s, Table 3): RIDC becomes the most energy-efficient (7,856 ± 398 mJ) because it avoids idle listening between beacons, TADC becomes the most expensive (9,102 ± 287 mJ) as its duty cycle rises to $\alpha \approx 24\%$ to keep pace with the queue, and PBDC's prediction accuracy falls from 94% to 72% yet it still outperforms SDC by about 6%. The radio's TX/RX

share of total energy rises to 67-71% under high traffic, and the sleep-mode contribution becomes negligible for every protocol.

Table 3. Energy breakdown under high traffic (λ = 2.0 pkt/s, 100-node random, mJ).

Protocol	Total energy (mJ)	TX	RX	Idle listen	Sleep	Overhead
SDC	8,734 ± 312	2,145	3,867	2,589	133	0
TADC	9,102 ± 287	2,312	4,234	2,401	98	57
RIDC	7,856 ± 398	1,987	3,654	1,923	156	136
PBDC	8,234 ± 365	2,089	3,945	2,034	124	42

Event-driven traffic which is spatially and temporally correlated favors PBDC (1,234 ± 89 mJ, exploiting the predictability of recurring events) and TADC (1,512 ± 76 mJ, raising its duty cycle only in active regions) over SDC (1,687 ± 54 mJ) and RIDC (1,598 ± 102 mJ, still burdened by beacon overhead despite handling bursts well); nodes within two hops of frequent event regions consume 2.3 times more energy than peripheral nodes, underlining the value of topology-aware adaptation. Grids result in 8-12% lower energy consumption, when deployed in compared to random deployment, in all protocols, due to shorter and more predictable routing paths (4.2 vs. 5.7 average hops for 100 nodes) and better load distribution.

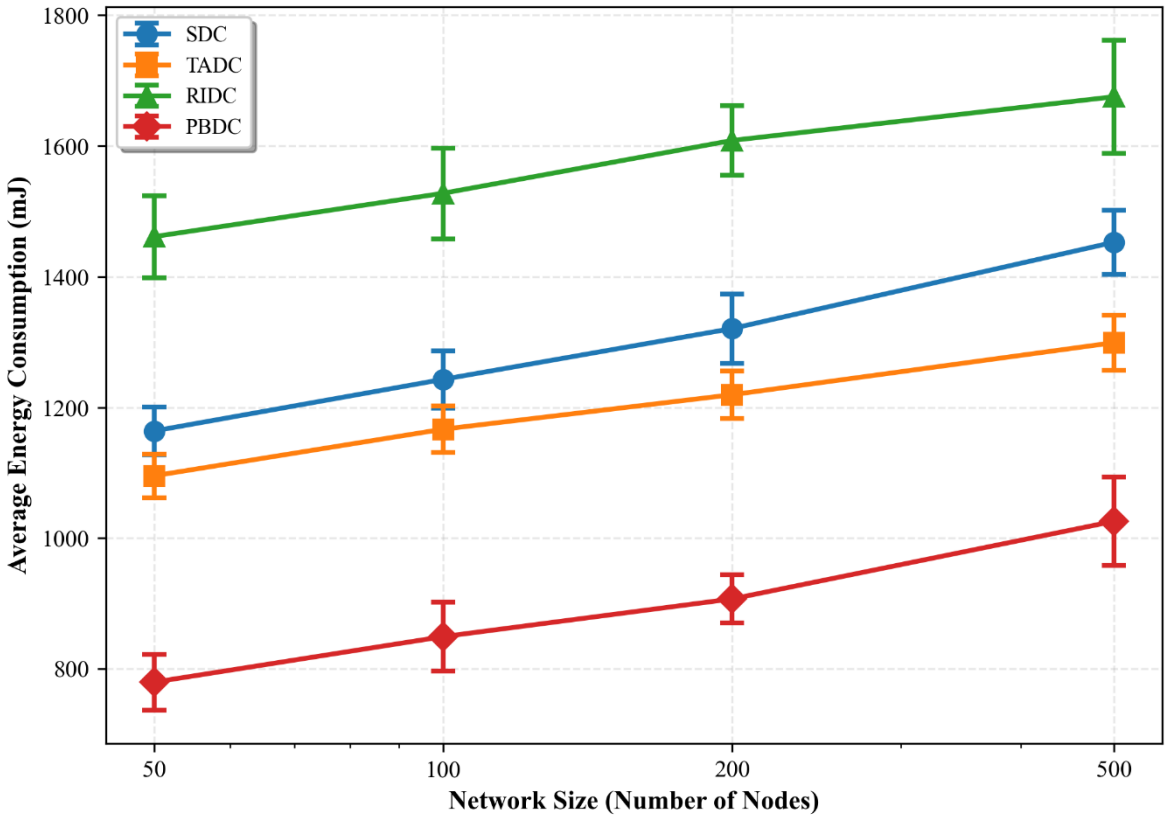


Figure 1. Average per-node energy consumption vs. network size (random topology, low traffic).

3.2 Latency and Packet Delivery

For a 100-node network at λ = 1.0 packets/s, average end-to-end latency was 2,847 ± 234 ms for SDC, 1,794 ± 198 ms for TADC (-37%), 1,456 ± 167 ms for RIDC (-49%), and 1,123 ± 289 ms for PBDC (-61% for correctly predicted packets). SDC latency linearly increases with the number of hops while RIDC latency scales sub-linearly, as it is influenced by the constant beacon period rather than the number of hops, and PBDC latency is bimodal, with 72% of packets delivered within 800ms, and the other 28% exceeding 3,000ms in case of prediction error. This is reflected in Packet delivery ratio (Table 2) which

is also higher for high traffic RIDC provides collision free, beacon-coordinated access, while for TADC the PDR improves by 15.7% over SDC due to reduction of buffer overflow; PBDC's PDR is restricted primarily by buffer overflow in mispredicted sleep interval.

Table 4. Packet delivery ratio (%) vs. traffic rate, 100-node random topology.

Traffic rate	SDC	TADC	RIDC	PBDC
λ = 0.1 pkt/s	98.7%	99.1%	99.3%	97.8%
λ = 0.5 pkt/s	94.3%	96.8%	97.2%	94.1%
λ = 1.0 pkt/s	85.7%	91.4%	93.6%	86.3%
λ = 2.0 pkt/s	73.2%	88.9%	91.2%	78.4%

Loss attribution (Table 5, high traffic) shows that each protocol fails differently: SDC's fixed schedule causes buffer overflow at intermediate nodes during bursts (62.3% of losses); TADC's more active radio increases collisions (35.2%) as it tries to avoid overflow; RIDC shifts most losses to channel error (62.1%), since beacons enable transmission without improving SNR; and PBDC still loses most packets to buffer overflow (55.8%) when nodes sleep through a mispredicted arrival. Spatially, per-node PDR degrades with hop count for every protocol from 97-99% at one hop to 65-81% at six or more hops and RIDC shows the most uniform spatial distribution (σ = 8.7%) while SDC is the most variable (σ = 15.3%), reflecting RIDC's more even, beacon-coordinated channel access (Figure 3).

Table 5. Packet-loss attribution under high traffic (100-node random topology).

Protocol	Buffer overflow	Collision	Channel error	Timeout
SDC	62.3%	28.4%	7.8%	1.5%
TADC	41.7%	35.2%	19.3%	3.8%
RIDC	18.9%	15.4%	62.1%	3.6%
PBDC	55.8%	22.1%	18.7%	3.4%

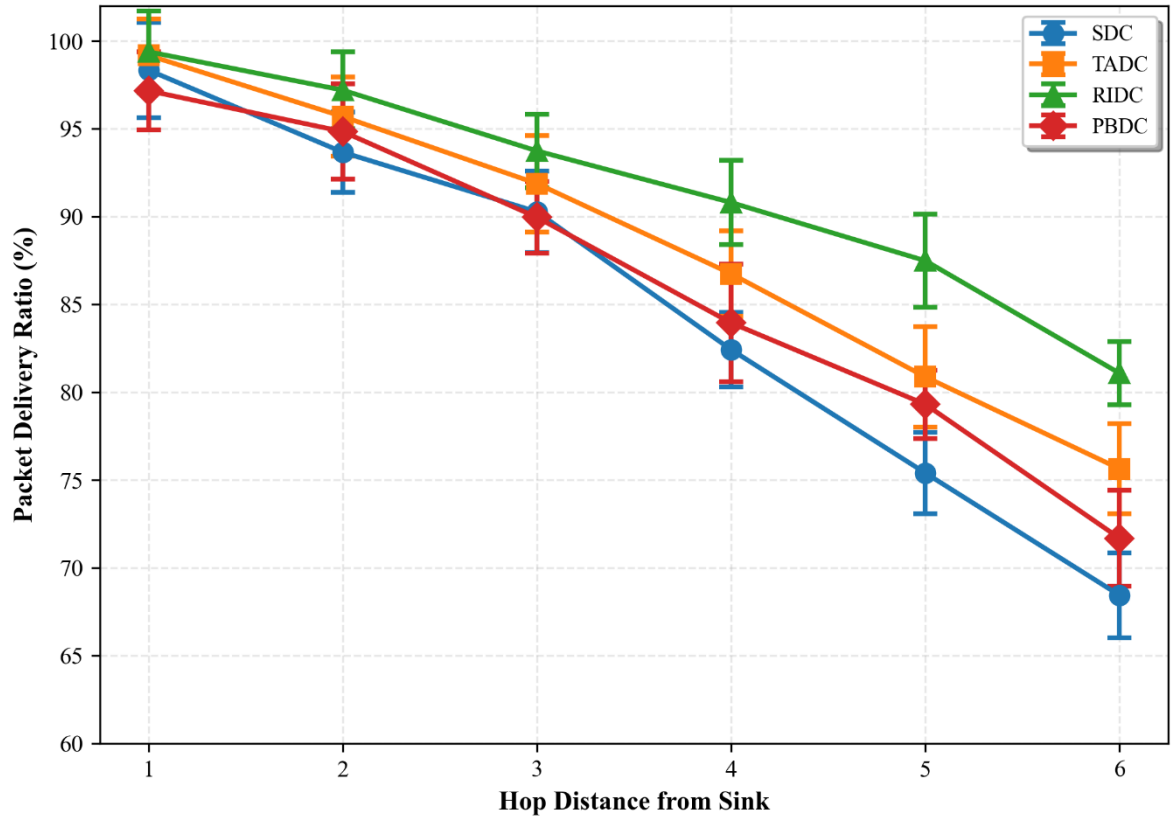


Figure 2. Spatial PDR variation by hop distance from the sink.

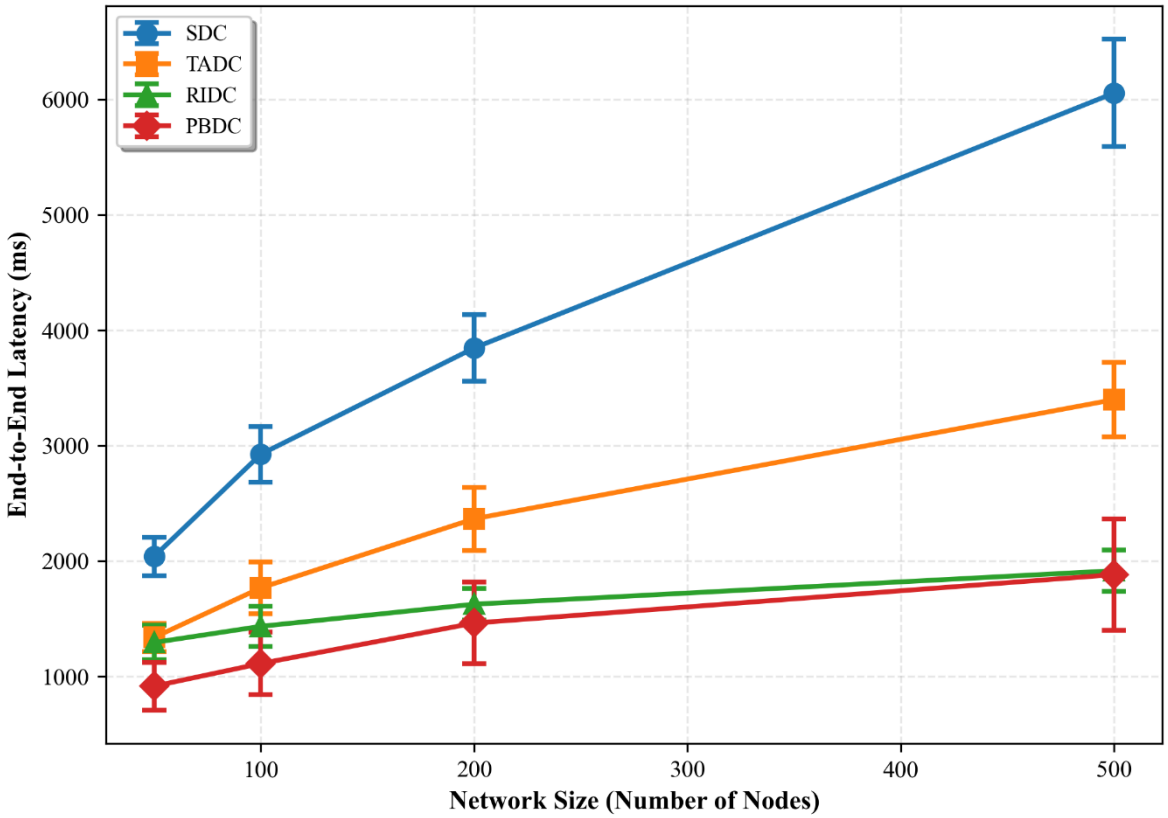


Figure 3. Average end-to-end latency vs. network size (λ = 1.0 packets/s).

3.3 Control Overhead and Network Lifetime

RIDC's beacon mechanism costs 45 µJ per transmission at a 500 ms period, i.e., about 7.8 J/day, or 12-18% of total node energy justified under high traffic by the PDR gains reported above, but wasteful when traffic is sparse. TADC's queue-monitoring and duty-cycle computation cost roughly 2 µJ per adaptation (every 5 s), under 0.5% of total energy; PBDC's EWMA prediction costs about 5 µJ per packet, or 3-5% of total energy at λ = 1.0 packets/s. Both adaptation overheads are therefore negligible next to the radio's own energy budget, confirming that the measured gains are not offset by computation cost.

Network lifetime, measured as time to first node failure (100-node random topology, λ = 0.5 packets/s, 5,000 mAh battery), was 38.7 ± 2.3 h for SDC, 42.3 ± 2.8 h for TADC (+9.3%), 35.2 ± 3.1 h for RIDC (-9%, due to beacon overhead on receivers), and 62.8 ± 5.7 h for PBDC (+62%), reflecting PBDC's ability to sleep more than 95% of the time under low, predictable traffic; time to 50% node death (network partition) followed the same ordering (64.1-89.4 h). Energy imbalance across nodes, measured by the coefficient of variation at t = 24 h, was lowest for SDC (0.23) and highest for PBDC (0.34), indicating that the same aggressive sleeping that extends PBDC's average lifetime also increases variance between nodes, its ratio of partition time to first-death time (1.42×) is the lowest of the four protocols, meaning its peripheral nodes fail in closer succession once the first one drains.

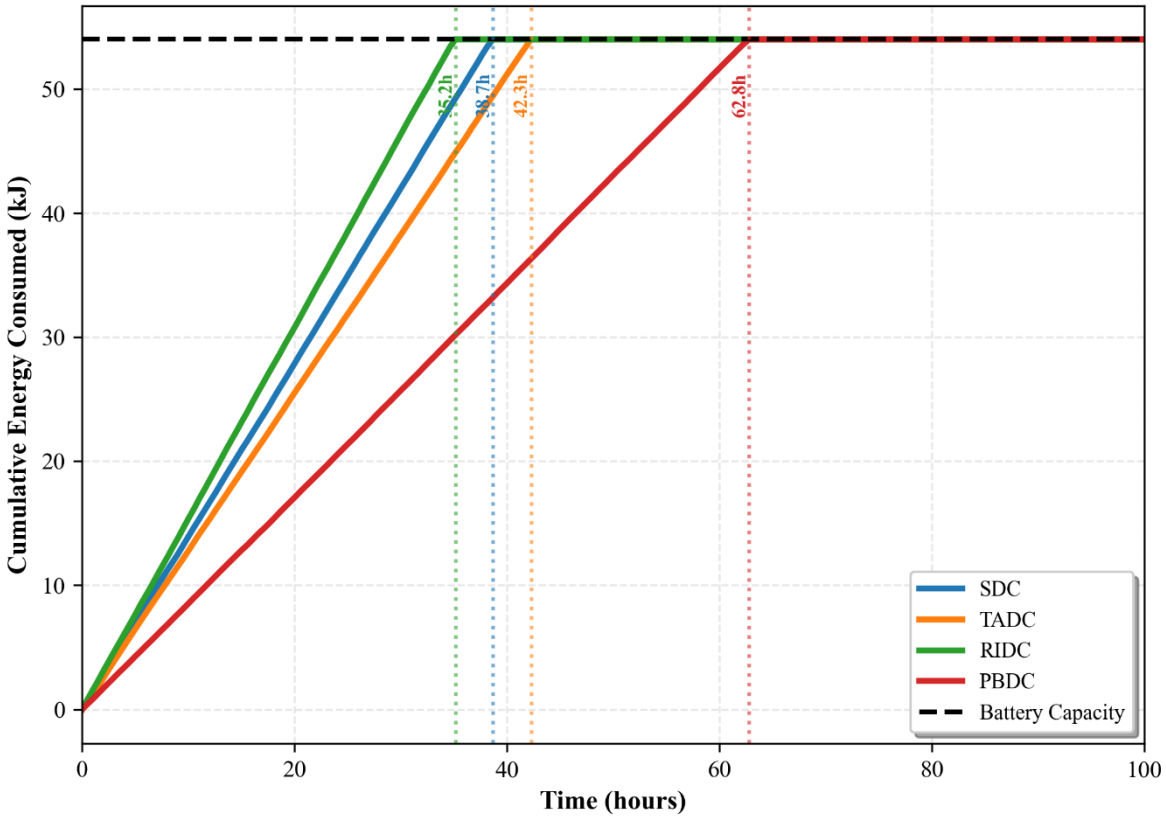


Figure 4. Network lifetime comparison (time to first node failure and 50% node death).

Scalability from 50 to 500 nodes (Table 6) showed RIDC degrading the least in latency (×1.43) and PDR (0.88 of baseline), while PBDC showed the largest relative increase in per-node energy (×1.31); grid topologies scaled better than random ones for every protocol (energy exponent 0.68 vs. 0.81; latency exponent 1.12 vs. 1.34; PDR degradation 8% vs. 24% from 50 to 500 nodes).

Table 6. Scalability of key metrics from 50 to 500 nodes (random topology).

Metric (500 vs. 50 nodes)	SDC	TADC	RIDC	PBDC
Energy per node (×)	1.23	1.18	1.15	1.31
Latency (×)	2.87	2.34	1.43	2.12
PDR (fraction of baseline)	0.76	0.84	0.88	0.78

3.4 Trade-offs and Protocol Selection Framework

These results confirm that no single protocol is optimal across all conditions (Figure 5). PBDC dominates in the energy-optimized regime (low, predictable traffic): its prediction accuracy reaches 94% for strictly periodic traffic (60 s period), yielding 32% energy savings and 62% longer lifetime, but falls to 72% for Poisson traffic (18% savings) and 68% for bursty events (12% savings), since false predictions waste energy on unnecessary wake-ups without any latency benefit. RIDC dominates the latency-optimized regime (high or bursty traffic) at a 12-22% energy premium. TADC occupies an intermediate position; a sensitivity analysis of its adaptation interval shows T_{adapt} = 1 s improves PDR by 3% at an 8% energy cost, T_{adapt} = 10 s saves 5% energy at a 7% PDR cost, and the chosen T_{adapt} = 5 s balances the two. Based on this trade-off structure, Table 7 proposes a protocol-selection framework linking traffic characteristics to a recommended protocol.

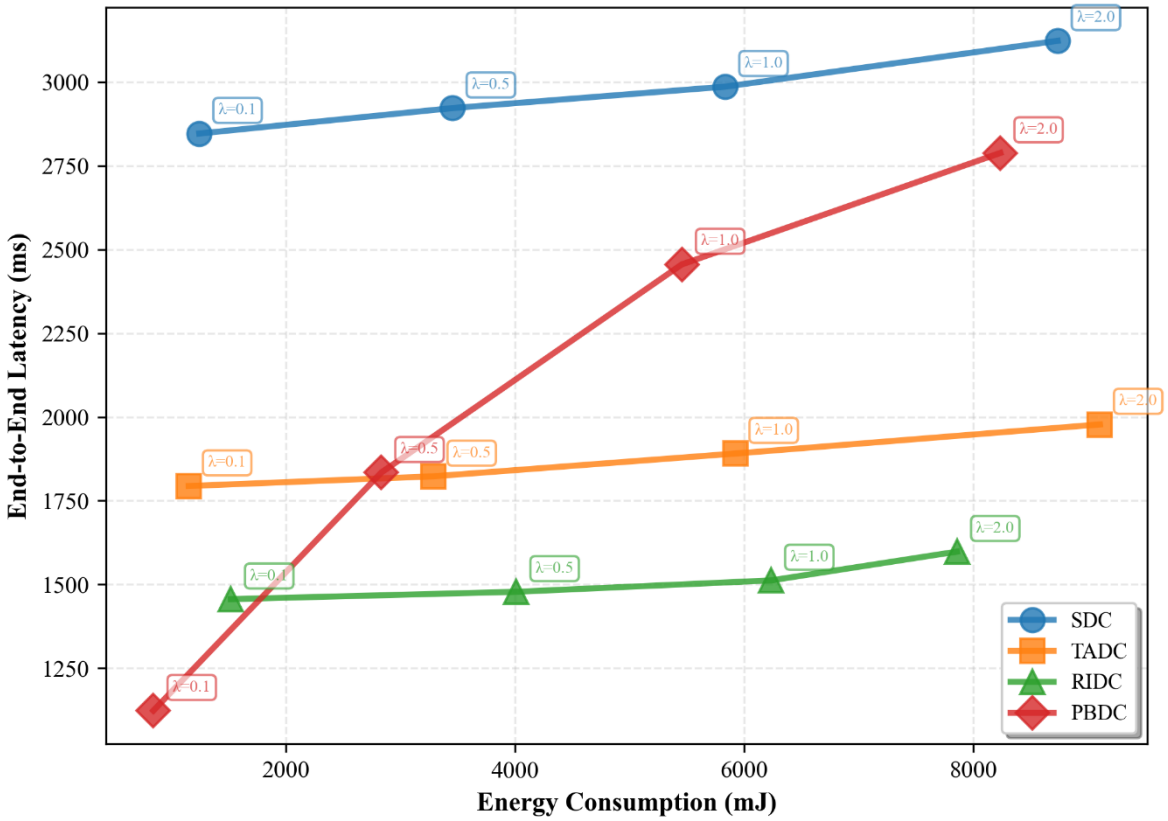


Figure 5. Pareto-frontier analysis of the energy-latency trade-off.

Table 7. Protocol-selection framework by application class.

Application class	Traffic profile	Recommendation	Rationale
Periodic environmental monitoring	Low rate, predictable	PBDC	Maximum lifetime gain (+62%), high prediction accuracy
Event-driven sensing	Bursty, spatially correlated	TADC	Adapts to bursts; PDR 91% vs. 86% for SDC
Real-time monitoring	Continuous, high rate	RIDC	Lowest latency (1,456 ms); highest PDR (93.6%)
Resource-constrained deployment	Mixed / low complexity budget	SDC	No adaptation overhead; predictable behavior

Dense networks (average node degree > 8) favor RIDC's collision-avoiding coordination, while sparse networks (degree < 4) benefit more from TADC/PBDC's local adaptivity; an intermediate degree of 6-8, as in this study's 100-node/100 m² configuration, was found to be near-optimal. In terms of implementation effort, SDC and RIDC require only timer- and beacon-based logic and are suitable even for constrained 8-bit microcontrollers, whereas TADC and, especially, PBDC require queue or history management better suited to 32-bit platforms; parameter sensitivity is also higher for the adaptive protocols (e.g., a ±0.1 change in PBDC's γ shifts energy by about ±12%, and a ±20% change in TADC's queue thresholds shifts PDR by about ±15%), suggesting self-tuning parameter selection as a valuable extension. In a heterogeneous deployment, sink-adjacent nodes could run RIDC (to absorb high relay traffic with bounded latency), intermediate nodes TADC (to track variable relay load), and peripheral nodes PBDC or SDC (to maximize lifetime under light traffic), a configuration this study did not simulate directly but that follows naturally from the single-protocol results.

These findings are broadly consistent with prior single-protocol evaluations reporting 7-62% adaptive gains over static baselines and confirming the energy-latency trade-off as a structural feature of duty-

cycled WSNs (Anastasi et al., 2009; Langendoen & Meier, 2010), while extending them through a direct, four-way comparison at a larger scale (up to 500 nodes, more than 5,000 runs) and with multiple traffic models, which most prior studies do not attempt simultaneously. Where this study's RIDC energy figures differ from more favorable results reported elsewhere, the discrepancy is attributable to a shorter beacon period (500 ms vs. 1,000 ms), a many-to-one rather than peer-to-peer traffic pattern, and differing sleep-power assumptions in the underlying radio model all of which affect the balance between beacon and idle-listening costs. The main limitations of this study are the assumption of a static topology (no node mobility), a simplified threshold-based channel-error model without fading, a single homogeneous radio and energy profile across all nodes, and application-layer traffic delivered directly to the sink without in-network aggregation; extending the analysis to mobile and heterogeneous deployments, hybrid traffic-aware/prediction-based adaptation, machine-learning-based traffic forecasting, cross-layer optimization with routing, energy-harvesting-aware duty cycling, and validation on physical testbeds are recommended as the most promising directions for future research.

4. CONCLUSION AND RECOMMENDATIONS

This study compared four duty-cycling protocols for wireless sensor networks, SDC, TADC, RIDC, and PBDC through more than 5,000 NS-3 simulation runs spanning network sizes of 50-500 nodes, two topologies, and three traffic patterns. On energy efficiency, PBDC performed best under low-to-moderate, predictable traffic (32% improvement over SDC), TADC saved 7-15% under low-to-moderate traffic while also improving latency and PDR at high traffic, and RIDC consumed 12-22% more energy than SDC except under sparse traffic. On latency, RIDC reduced average end-to-end latency by 49% through beacon coordination, PBDC achieved the lowest latency for correctly predicted traffic but with high variance, and TADC reduced latency by 30-40% relative to SDC across conditions. On reliability, RIDC achieved the highest PDR (91.2% at high traffic) and TADC improved 15.7 percentage points over SDC's 73.2%, while PBDC's PDR suffered under unpredictable traffic. On network lifetime, PBDC's aggressive sleep schedule extended time to first node failure by 62%, though adaptive protocols in general showed higher energy imbalance (coefficient of variation 23-34%) than SDC, suggesting load-balancing extensions could further improve lifetime for all four protocols. No protocol is dominant in every scenario, and protocol selection depends on the traffic and latency requirements of the target application: PBDC for periodic monitoring where lifetime is most important, TADC for event-driven applications, where bounded delay is important for achieving a balance between energy, delay and reliability, RIDC for real-time applications where bounded delay is more significant than the added energy, and SDC for applications where implementation simplicity is most important. The type of network also is important, and RIDC is better in dense networks because of its collision avoidance properties, while TADC and PBDC are preferred in sparse networks because of their local adaptivity; and grid topologies perform better than random networks for any protocol studied. The results presented here provide actual, measurable data for the selection or design of a duty-cycling mechanism for WSN and for further WSN duty-cycling protocol development and standardization, while the simulation technique described here can be reused to assess future duty-cycling protocols, such as hybrid, learning-based and energy-harvesting-aware duty-cycling designs.

ACKNOWLEDGEMENTS

The author declares no funding was received for this study and no competing interests.

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GIDA SOĞUK ZİNCİRİ LOJİSTİĞİNDE DİJİTALLEŞME VE SÜRDÜRÜLEBİLİRLİK: BİBLİYOMETRİK VE TEMATİK BİR ANALİZ

DIGITALIZATION AND SUSTAINABILITY IN FOOD COLD CHAIN LOGISTICS: A BIBLIOMETRIC AND THEMATIC ANALYSIS

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ÖZET

Bu çalışmanın amacı, gıda soğuk zinciri lojistiğinde dijitalleşme ve sürdürülebilirlik kesişiminde gelişen bilimsel literatürün yapısını, büyüme eğilimini ve tematik yönelimlerini bibliyometrik yöntemlerle incelemektir. Web of Science Core Collection veri tabanında 2010–2025 dönemini kapsayan konu alanı temelli bir tarama gerçekleştirilmiş; İngilizce yayımlanan makale ve derlemeler, çalışma kapsamına alınmıştır. Arama ve filtreleme işlemi sonucunda 200 yayına ulaşılmıştır. Bu yayınların 6'sının erken erişim yılı 2025 olmakla birlikte nihai yayın yılı 2026 olarak belirlendiğinden, söz konusu yayınlar değerlendirme dışı bırakılmıştır. Kalan 194 yayın, başlık, özet ve yazar anahtar kelimeleri temelinde değerlendirilmiştir. Bu değerlendirme sonucunda, gıda ve tarım-gıda, soğuk zincir veya bozulabilir ürün lojistiği, dijital teknoloji ve sürdürülebilirlik boyutlarını yeterince karşılamayan 39 yayın kapsam dışında bırakılmış, nihai analiz 155 yayın üzerinden gerçekleştirilmiştir. Nihai veri setinde performans ve atıf analizleri yürütülmüş, yazar anahtar kelimesi eş-oluşum ve bibliyografik bağlantı ağları VOSviewer ile oluşturulmuş, ayrıca dönemsel tematik evrim incelenmiştir. Bulgular, yayın sayısının 2021 sonrasında belirgin biçimde arttığını ve 2025 yılında 49 yayına ulaştığını göstermektedir. En yüksek yayın sayısına sahip kaynaklar Foods ve Sustainability (10'ar yayın), Food Control (9 yayın) ve Trends in Food Science & Technology (8 yayın) olarak belirlenmiştir. En sık kullanılan yazar anahtar kelimeleri, soğuk zincir (35), gıda israfı (15), sürdürülebilirlik (13), Nesnelerin İnterneti (12) ve soğuk zincir lojistiği (11) olmuştur. VOSviewer eş-oluşum ağı 35 anahtar kelimeyi 7 kümede, bibliyografik bağlantı ağı ise en büyük bağlı bileşeni oluşturan 144 yayını 9 kümede gruplamıştır. Tematik bulgular, alanın sensör ve sıcaklık izleme odaklı erken dönem çalışmalardan Nesnelerin İnterneti, blokzincir, yapay zekâ ve dijital ikiz temelli, sürdürülebilirlik odaklı karar destek araştırmalarına doğru evrildiğini göstermektedir. Genel olarak bulgular, dijital teknolojilerin gıda soğuk zincirinde yalnızca izleme ve kontrol aracı olmaktan çıkarak sürdürülebilirlik odaklı ve veriye dayalı karar verme süreçlerinin temel bileşenlerinden biri haline geldiğini ortaya koymaktadır.

Anahtar Kelimeler: Soğuk Zincir Lojistiği, Dijitalleşme, Sürdürülebilirlik, Bibliyometrik Analiz.

ABSTRACT

This study examines the structure, growth trend, and thematic orientations of the literature at the intersection of digitalization and sustainability in food cold chain logistics using bibliometric methods. A topic-based search covering 2010–2025 was conducted in the Web of Science Core Collection, and English-language articles and reviews were included. The search and filtering process yielded 200 publications. Six publications had an Early Access year of 2025 but a final publication year of 2026 and were therefore excluded. The remaining 194 publications were evaluated based on titles, abstracts, and author keywords. Following this evaluation, 39 publications that did not sufficiently address food and agri-food, cold chain or perishable product logistics, digital technology, and sustainability were excluded, resulting in a final dataset of 155 publications. Performance and citation analyses were conducted; author-keyword co-occurrence and bibliographic coupling networks were created using VOSviewer, and thematic evolution was additionally examined across periods. The number of publications increased markedly after 2021, reaching 49 in 2025. The sources with the highest number of publications were Foods and Sustainability (10 publications each), Food Control (9 publications), and Trends in Food Science & Technology (8 publications). The most frequent author keywords were cold chain (35), food waste (15), sustainability (13), Internet of Things (12), and cold chain logistics (11). The VOSviewer co-occurrence network grouped 35 keywords into 7 clusters, while the bibliographic coupling network grouped 144 publications in the largest connected component into 9 clusters. The thematic findings indicate a shift from early studies focused on sensor- and temperature-based monitoring toward research on sustainability-oriented decision support based on the Internet of Things,

blockchain, artificial intelligence, and digital twins. Overall, the findings show that digital technologies have moved beyond monitoring and control functions to become key components of sustainability-oriented and data-driven decision-making in food cold chain logistics.
Keywords: Cold Chain Logistics, Digitalization, Sustainability, Bibliometric Analysis.

GİRİŞ

Gıda soğuk zinciri lojistiği, sıcaklığa duyarlı ürünlerin kalite, güvenlik ve raf ömrünün üretimden nihai tüketiciye kadar korunmasını gerektiren, operasyonel açıdan hassas ve veri yoğun bir lojistik sistemdir. Zincirin herhangi bir aşamasında ortaya çıkan sıcaklık sapmaları ürün kalitesinde azalma, gıda kaybı ve güvenlik riskleri doğurabilmektedir. Bu nedenle sıcaklık ve çevresel koşulların kesintisiz izlenmesi, kayıt altına alınması ve lojistik kararlarla ilişkilendirilmesi soğuk zincir yönetiminin temel sorunlarından biridir. RFID, kablosuz sensör ağları ve gerçek zamanlı izleme sistemleri bu gereksinime yönelik başlıca dijital araçlar arasında yer almaktadır (Badia-Melis, Mc Carthy, Ruiz-Garcia, Garcia-Hierro, & Robla Villalba, 2018).

Dijitalleşmenin soğuk zincirdeki rolü zaman içinde yalnızca veri toplama ve izleme işlevleriyle sınırlı kalmamış; Nesnelerin İnterneti (IoT), blokzincir, yapay zekâ, makine öğrenmesi ve dijital ikiz gibi teknolojilerin kullanımıyla karar destek, izlenebilirlik, tahmin ve optimizasyon boyutlarına doğru genişlemiştir. IoT tabanlı uygulamalar soğuk zincir risklerinin gerçek zamanlı izlenmesine olanak sağlarken (Tsang et al., 2018), veri analitiği lojistik süreçlerde risk değerlendirmesi ve karar verme kapasitesini güçlendirmektedir (Chaudhuri, Dukovska-Popovska, Subramanian, Chan, & Bai, 2018). Dijital ikiz yaklaşımı ise fiziksel ürün ve lojistik koşullara ait sensör verilerini model tabanlı tahminlerle birleştirerek ürün kalitesi ve kalan raf ömrü gibi değişkenlerin öngörülmesine katkı sağlayabilmektedir (Defraeye et al., 2021).

Bu teknolojik dönüşüm, sürdürülebilirlik hedefleriyle de giderek daha güçlü biçimde ilişkilendirilmektedir. Gıda kaybının azaltılması, enerji ve kaynak kullanımının iyileştirilmesi, izlenebilirliğin güçlendirilmesi ve daha dayanıklı tedarik zincirlerinin geliştirilmesi dijital soğuk zincir araştırmalarının temel çıktıları arasında yer almaktadır. Bununla birlikte literatür; gıda bilimi, lojistik, mühendislik, bilgi sistemleri ve sürdürülebilirlik gibi farklı disiplinlere dağılmış durumdadır. Bu da alanın bilimsel gelişiminin, kavramsal çekirdeğinin ve zaman içinde değişen araştırma gündeminin bütüncül olarak değerlendirilmesini gerekli kılmaktadır.

Bibliyometrik analiz, geniş bir literatür kümesinin yayın eğilimlerini, etkili kaynaklarını, anahtar kavramlarını ve bilimsel bağlantılarını nicel olarak incelemeye olanak sağlamaktadır (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021). Ağ tabanlı bilim haritalama araçları ise anahtar kelimeler veya yayınlar arasındaki ilişkileri görselleştirerek literatürdeki tematik yapılanmayı ortaya koyabilmektedir. VOSviewer, bibliyometrik ağların oluşturulması, kümelenmesi ve görselleştirilmesi amacıyla yaygın olarak kullanılan bir yazılımdır (van Eck & Waltman, 2010).

Bu çalışmanın amacı, 2010–2025 döneminde gıda soğuk zinciri lojistiğinde dijitalleşme ve sürdürülebilirlik kesişiminde gelişen bilimsel literatürün büyüme eğilimini, kaynak ve ülke dağılımını, atıf etkisini, anahtar kelime yapısını ve bibliyografik bağlantı örüntülerini incelemektir. Çalışma ayrıca dönemsel anahtar kelime görünürlüğünü değerlendirerek alanın sensör tabanlı izleme yaklaşımlarından daha bütünleşik, veri temelli ve sürdürülebilirlik odaklı karar destek çözümlerine doğru nasıl evrildiğini ortaya koymayı amaçlamaktadır.

MATERYAL VE YÖNTEM

Çalışmanın veri kaynağı Web of Science (WoS) Core Collection'dır. Tarama 9 Eylül 2026 tarihinde gerçekleştirilmiş ve tamamlanmış yayın yıllarının karşılaştırılabilmesi amacıyla analiz dönemi 2010–2025 ile sınırlandırılmıştır. Belge türü olarak Article ve Review Article, dil olarak English filtreleri uygulanmıştır. Konu alanı aramasında soğuk zincir, gıda/bozulabilir ürün, dijital teknoloji ve sürdürülebilirlik kavramlarını aynı sorguda bir araya getiren aşağıdaki TS sorgusu kullanılmıştır:

TS=(("cold chain" OR "cold supply chain" OR "cold-chain logistics" OR "temperature-controlled logistics" OR "refrigerated logistics" OR "refrigerated supply chain") AND (food* OR agrifood OR "agri-food" OR perishable* OR "fresh food") AND (digital* OR "digital transformation" OR IoT OR "internet of things" OR blockchain OR RFID OR sensor* OR "real-time monitoring" OR traceability OR "artificial intelligence" OR "machine learning" OR "big data" OR automation OR "digital twin*")

AND (sustainab* OR environment* OR "energy efficiency" OR carbon OR emission* OR "food waste" OR resilien* OR circular*)).

Arama ve filtreleme işlemi sonucunda 200 yayına ulaşılmıştır. Tam kayıtların kontrolünde 6 yayının Early Access yılı 2025 olmasına rağmen nihai yayın yılının (PY) 2026 olduğu belirlenmiş ve bu kayıtlar dönem dışında bırakılmıştır. Kalan 194 yayın başlık, özet ve yazar anahtar kelimeleri üzerinden içerik uygunluğu açısından değerlendirilmiştir. Nihai dahil etme için dört unsurun yeterince doğrudan bulunması aranmıştır: (i) gıda veya tarım-gıda bağlamı, (ii) soğuk zincir ya da bozulabilir ürün lojistiği, (iii) dijital teknoloji/veri/izleme bileşeni ve (iv) sürdürülebilirlik, enerji, gıda kaybı, çevresel performans veya dayanıklılık bağlantısı. Bu değerlendirme sonunda 39 yayın kapsam dışında bırakılmış ve nihai veri seti 155 yayından oluşmuştur. WoS kimliği ve DOI düzeyinde tekrar kayıt saptanmamıştır. Veri seçim ve uygunluk taraması süreci Tablo 1'de özetlenmektedir.

Performans analizinde yıllık yayın sayıları, kaynak ve ülke katılımı, WoS atıf sayıları ve yazar anahtar kelimesi frekansları hesaplanmıştır. Ülke bulguları tam sayım yaklaşımıyla değerlendirilmiş; çok ülkeli yayınlarda her ülkenin katkısı ayrı katılım olarak sayılmıştır. WoS atıf değerleri 9 Eylül 2026 tarihindeki kümülatif sayıları yansıtmaktadır.

Anahtar kelime eş-oluşum ve bibliyografik bağlantı analizleri VOSviewer yazılımında gerçekleştirilmiştir. Anahtar kelime analizinde analiz türü Co-occurrence, birim Author keywords ve sayım yöntemi Full counting olarak seçilmiş; en az 3 yayında görülen anahtar kelimeler ağa dahil edilmiştir. Terim varyantları VOSviewer thesaurus dosyasıyla standartlaştırılmıştır. Bu kapsamda IoT/Internet of Things, AI/artificial intelligence, digital twins/digital twin, cold-chain/cold chain, cold supply chain/cold chain, cold-chain logistics/cold chain logistics ve food loss and waste/food waste gibi açık varyantlar birleştirilmiştir. Bu işlem sonunda 35 anahtar kelimeden oluşan ağ 7 kümeye ayrılmış; ağda 123 bağlantı ve 175 toplam bağlantı gücü oluşmuştur.

Bibliyografik bağlantı analizinde analiz türü Bibliographic coupling, birim Documents ve sayım yöntemi Full counting olarak seçilmiştir. Minimum belge atıf eşiği 0 tutulmuş ve 155 yayının tamamı başlangıçta analize alınmıştır. VOSviewer, 155 yayının 144'ünün tek bir en büyük bağlı bileşen oluşturduğunu belirlemiş; ağ görselleştirmesi ve kümeleme bu 144 yayın üzerinden yürütülmüştür. Nihai bibliyografik bağlantı ağı 9 küme, 2409 bağlantı ve 5573 toplam bağlantı gücünden oluşmuştur. Ağ kümelerine verilen tematik adlar yazılım tarafından otomatik üretilmemiş; küme üyelerinin yayın başlıkları ve araştırma içerikleri birlikte değerlendirilerek yorumlanmıştır.

Tematik evrim, alanın zaman içindeki kavramsal değişimini göstermek amacıyla 2010–2017, 2018–2021, 2022–2023 ve 2024–2025 dönemleri altında anahtar kelime görünürlüğünün karşılaştırılmasıyla değerlendirilmiştir. Bu dönemsel inceleme, VOSviewer ağ sonuçlarını tamamlayıcı betimsel bir analiz olarak kullanılmıştır.

Tablo 1. Veri Seçimi ve Uygunluk Taraması

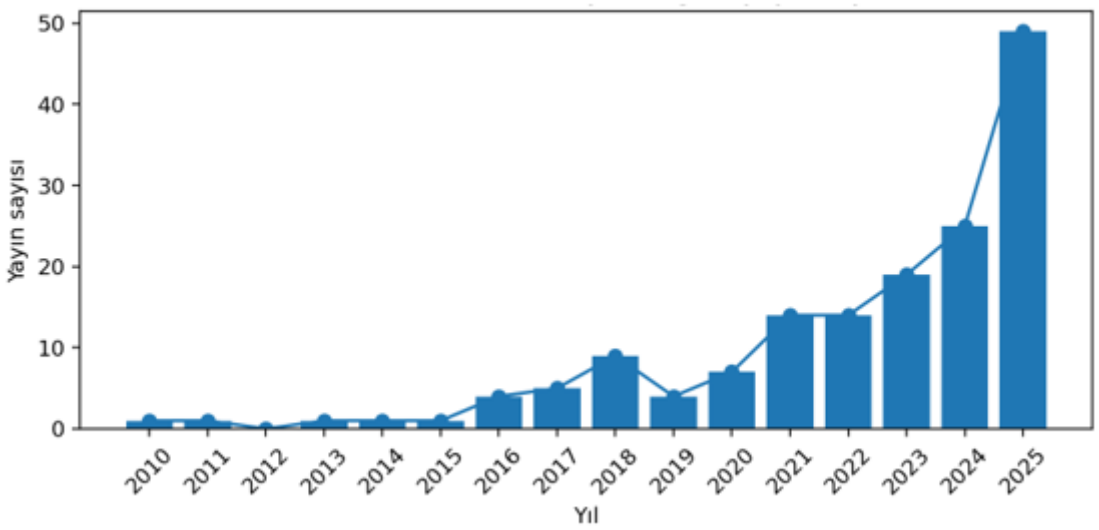
Aşama	Yayın	Açıklama
WoS filtre sonucu	200	2010–2025; Article/Review Article; English
Nihai yayın yılı 2026	−6	Early Access=2025; PY=2026
İçerik değerlendirme havuzu	194	Başlık, özet ve yazar anahtar kelimeleri
Kapsam dışında bırakılan	−39	Dört kapsam eksenini yeterince karşılamayan
Nihai analiz kümesi	155	Performans, atıf ve ağ analizleri

BULGULAR VE TARTIŞMA

Yayın Eğilimi Ve Üretim Yapısı

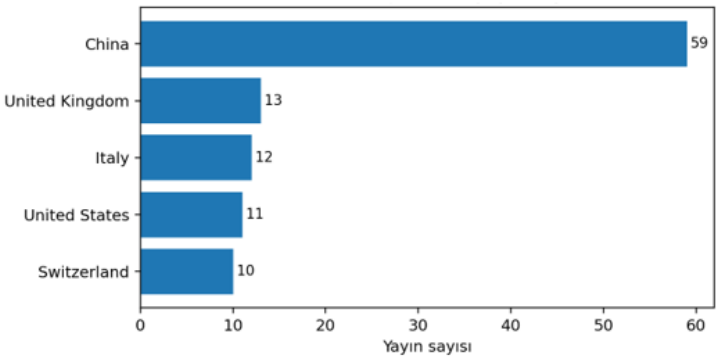
Nihai 155 yayının yıllara göre dağılımı, alanın özellikle 2021 sonrasında hızla genişlediğini göstermektedir. 2010–2017 döneminde 14, 2018–2021 döneminde 34, 2022–2023 döneminde 33 ve 2024–2025 döneminde 74 yayın bulunmaktadır. Yıllık yayın sayısı 2021'de 14, 2022'de 14, 2023'te 19, 2024'te 25 ve 2025'te 49'a yükselmiştir. 2024–2025 döneminin tek başına toplam veri setinin yaklaşık yarısını oluşturması, dijitalleşme-sürdürülebilirlik kesişimindeki araştırma ilgisinin son iki yılda belirgin

biçimde yoğunlaştığını göstermektedir. Yıllara göre yayın sayısının dağılımı ve artış eğilimi Şekil 1'de sunulmaktadır.



Şekil 1. 2010–2025 Döneminde Yıllara Göre Yayın Sayısının Dağılımı

Kaynak dağılımında Foods ve Sustainability 10'ar yayınla ilk sırayı paylaşmakta; Food Control 9, Trends in Food Science & Technology 8 ve Journal of Food Process Engineering 4 yayınla bu kaynakları izlemektedir. Ülke katılımında Çin 59 yayınla öne çıkarken Birleşik Krallık 13, İtalya 12, ABD 11, İsviçre 10 ve Hindistan 9 yayında yer almaktadır. Ülke değerlerinin toplamının 155'i aşabilmesi, çok ülkeli yayınlarda her ülkenin ayrı katılım olarak sayılmasından kaynaklanmaktadır. En üretken ülkelerin yayın sayıları Şekil 2'de görselleştirilmiştir. En üretken beş kaynak ve ülke birlikte Tablo 2'de sunulmaktadır.



Şekil 2. En Üretken Beş Ülkenin Yayın Sayılarına Göre Dağılımı

Tablo 2. En Üretken Beş Kaynak ve Ülke

En üretken kaynak	**Yayın**	**Ülke**	**Yayın**
Foods	10	China	59
Sustainability	10	United Kingdom	13
Food Control	9	Italy	12
Trends in Food Science & Technology	8	United States	11
Journal of Food Process Engineering	4	Switzerland	10

Atıf Etkisi ve Temel Çalışmalar

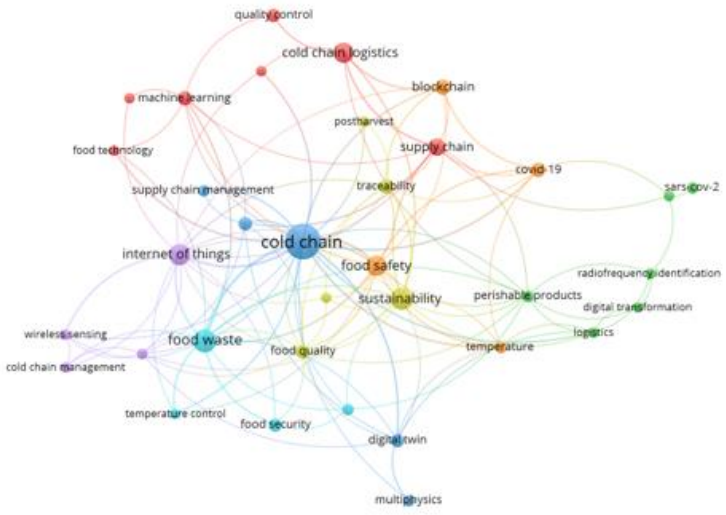
Nihai veri setinde en yüksek WoS atıfı alan çalışma Ndraha, Hsiao, Vlajic, Yang ve Lin (2018) tarafından yayımlanan time-temperature abuse derlemesidir (305 atıf). Bunu Han et al. (2021) tarafından hazırlanan taze tarımsal ürünlerde soğuk zincir lojistiği derlemesi (290), Cai et al. (2021) tarafından geliştirilen gerçek zamanlı kablosuz gıda kalite değerlendirmesi çalışması (214), Badia-Melis et al. (2018) tarafından hazırlanan soğuk zincir izleme derlemesi (190) ve Singh, Gunasekaran ve Kumar (2018) tarafından geliştirilen 3PL seçimi çalışması (168) izlemektedir. Atıf değerleri kümülatif olduğundan daha eski yayınların atıf biriktirmek için daha uzun süreye sahip olduğu dikkate alınmalıdır. Nihai veri setinde en çok atıf alan ilk beş yayın Tablo 3'te sunulmaktadır.

Tablo 3. Nihai Veri Setinde En Çok Atıf Alan İlk Beş Yayın

Çalışma	Yıl	WoS atıf
Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations	2018	305
A comprehensive review of cold chain logistics for fresh agricultural products: Current status, challenges, and future trends	2021	290
Integration of a porous wood-based triboelectric nanogenerator and gas sensor for real-time wireless food-quality assessment	2021	214
New trends in cold chain monitoring applications - A review	2018	190
Third party logistics (3PL) selection for cold chain management: a fuzzy AHP and fuzzy TOPSIS approach	2018	168

Yazar Anahtar Kelimeleri ve VOSviewer Eş-Oluşum Ağı

Yazar anahtar kelimeleri alanın kavramsal çekirdeğini göstermektedir. Standartlaştırma sonrasında en sık kullanılan terim cold chain (35) olmuş; bunu food waste (15), sustainability (13), internet of things (12), cold chain logistics (11), food safety (11), supply chain (8), blockchain (7), machine learning (6), traceability (6), artificial intelligence (5) ve digital twin (5) izlemiştir. Eş-oluşum ağı, bu kavramların tek bir homojen yapıdan ziyade birbirine temas eden 7 alt temada örgütlendiğini göstermiştir. Anahtar kelimeler arasındaki ağ yapısının görsel haritası Şekil 3'te verilmektedir. Eş-oluşum kümelerinin büyüklükleri, yorumlanan temaları ve başlıca anahtar kelimeleri Tablo 4'te özetlenmektedir.



Şekil 3. VOSviewer Yazar Anahtar Kelimesi Eş-Oluşum Ağı Haritası (35 Öğe, 7 Küme)

Tablo 4. VOSviewer Yazar Anahtar Kelimesi Eş-Oluşum Kümeleri (35 Öğe, 7 Küme)

Küme	Öğe	Yorumlanan tema	Başlıca anahtar kelimeler
1	7	Makine öğrenmesi destekli soğuk zincir kalite ve tazelik yönetimi	cold chain logistics; machine learning; quality control; supply chain; wireless sensor network
2	6	Dijital dönüşüm, RFID ve bozulabilir ürün lojistiği	digital transformation; logistics; perishable products; radiofrequency identification; SARS-CoV-2
3	5	Soğuk zincirde yapay zekâ, dijital ikiz ve model tabanlı yönetim	artificial intelligence; cold chain; digital twin; multiphysics; supply chain management
4	5	Sürdürülebilirlik, izlenebilirlik ve ürün kalitesi	sustainability; traceability; food quality; postharvest; blockchain technology
5	4	IoT tabanlı izleme ve raf ömrü yönetimi	internet of things; shelf life; wireless sensing; cold chain management
6	4	Gıda israfı, gıda güvencesi ve sıcaklık kontrollü tedarik zinciri	food waste; food security; food supply chain; temperature control
7	4	Gıda güvenliği, blokzincir ve pandemi dönemi sıcaklık izleme	blockchain; food safety; COVID-19; temperature

Eş-oluşum ağındaki 7 küme, gıda soğuk zinciri literatürünün birbirini tamamlayan ancak farklılaşan araştırma eksenlerine sahip olduğunu göstermektedir. Birinci küme, cold chain logistics, machine learning, quality control, freshness assessment ve wireless sensor network kavramlarını bir araya getirerek makine öğrenmesi destekli kalite ve tazelik yönetimine işaret etmektedir. İkinci küme digital transformation, radiofrequency identification, logistics ve perishable products etrafında dijital dönüşüm ve bozulabilir ürün lojistiğini temsil etmektedir. Üçüncü kümede ağın en sık kullanılan terimi olan cold chain; artificial intelligence, digital twin, multiphysics ve supply chain management ile birlikte yer almakta ve model tabanlı yönetim yaklaşımını öne çıkarmaktadır. Dördüncü küme sustainability, traceability, food quality, postharvest ve blockchain technology kavramlarını sürdürülebilirlik, izlenebilirlik ve ürün kalitesi ekseninde birleştirmektedir. Beşinci kümede internet of things, shelf life, wireless sensing ve cold chain management, IoT tabanlı izleme ve raf ömrü yönetimi temasını oluşturmaktadır. Altıncı küme food waste, food security, food supply chain ve temperature control kavramlarıyla gıda israfı, gıda güvencesi ve sıcaklık kontrollü tedarik zinciri ilişkisini yansıtmaktadır. Yedinci küme ise food safety, blockchain, COVID-19 ve temperature kavramlarını bir araya getirerek gıda güvenliği, blokzincir ve pandemi dönemi sıcaklık izleme temasını göstermektedir. Bu tematik adlandırmalar VOSviewer tarafından otomatik verilmemiş, küme üyelerinin birlikte değerlendirilmesiyle yorumlanmıştır.

Tematik Evrim

Dönemsel inceleme, 2010–2017 döneminde cold chain, wireless sensor network ve freshness assessment kavramlarının öne çıktığını göstermektedir. 2018–2021 döneminde food safety, internet of things, traceability ve blockchain görünürlüğü artmıştır. 2022–2023 döneminde food waste, sustainability ve COVID-19/SARS-CoV-2 ile ilişkili temalar belirginleşmiştir. 2024–2025 döneminde

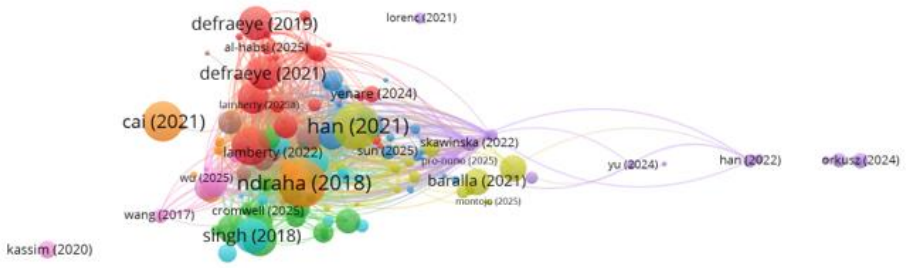
ise cold chain logistics, artificial intelligence, supply chain ve digital twin gibi kavramlar daha görünür hâle gelmiştir. Bu değişim, alanın sensör tabanlı izleme altyapısından daha bütünleşik, veri temelli ve sürdürülebilirlik odaklı karar destek çözümlerine doğru genişlediğini göstermektedir. Dönemsel tematik evrim Tablo 5'te özetlenmektedir.

Tablo 5. Dönemsel Tematik Evrim

Dönem	Öne çıkan kavramlar	Genel yönelim
2010–2017	cold chain; wireless sensor network; freshness assessment	Sensör tabanlı izleme ve tazelik değerlendirmesi
2018–2021	food safety; internet of things; traceability; blockchain	Bağlantılı izleme, izlenebilirlik ve veri bütünlüğü
2022–2023	food waste; sustainability; COVID-19/SARS-CoV-2	Kayıp azaltma, sürdürülebilirlik ve dayanıklılık
2024–2025	cold chain logistics; artificial intelligence; supply chain; digital twin	AI/dijital ikiz destekli bütünleşik karar verme

VOSviewer Bibliyografik Bağlantı Ağı

Bibliyografik bağlantı analizi 155 yayının ortak atıf kaynakları temelindeki yakınlığını incelemiştir. Minimum atıf eşiği 0 olarak belirlendiğinde tüm 155 yayın analize uygun bulunmuş, ancak VOSviewer en büyük bağlı bileşenin 144 yayından oluştuğunu göstermiştir. Bu nedenle ağ ve küme yapısı 144 yayın üzerinden değerlendirilmiştir. Ağda 2409 bağlantı ve 5573 toplam bağlantı gücü bulunmuş; yayınlar 9 kümeye ayrılmıştır. En büyük bağlı bileşenin dışında kalan 11 yayın nihai örneklemden çıkarılmamış, yalnızca bibliyografik bağlantı haritasının bağlı bileşeninde yer almamıştır. Bibliyografik bağlantı ağının görsel haritası Şekil 4'te sunulmaktadır. Dokuz bibliyografik bağlantı kümesinin büyüklükleri ve yorumlanan tematik odakları Tablo 6'da sunulmaktadır.



Şekil 4. VOSviewer Bibliyografik Bağlantı Ağı Haritası (En Büyük Bağlı Bileşen: 144 Yayın, 9 Küme)

Tablo 6. VOSviewer Bibliyografik Bağlantı Kümeleri (En Büyük Bağlı Bileşen: 144 Yayın, 9 Küme)

Küme	Yayın	Yorumlanan tematik odak	Örnek içerik
1	25	Dijital ikiz, fizik tabanlı modelleme ve taze ürün kalite yönetimi	Dijital ikizler, fizik tabanlı kalite tahmini, reefer konteynerler, gıda kaybı
2	22	IoT/RFID tabanlı izleme, izlenebilirlik ve soğuk zincir risk yönetimi	RFID, IoT risk izleme, cold-chain break detection, traceability, data analytics

Küme	Yayın	Yorumlanan tematik odak	Örnek içerik
3	22	Yapay zekâ, akıllı kalite kontrolü ve Endüstri 4.0 tabanlı dijitalleşme	Yapay zekâ, esnek sensörler, IIoT, akıllı kalite kontrol, düşük karbonlu lojistik
4	16	Blokzincir, dijital izlenebilirlik ve sürdürülebilir soğuk zincir yönetimi	Blockchain, dijital kimlik, traceability, sürdürülebilirlik, optimizasyon
5	16	Pandemi, gıda güvenliği ve soğuk zincir dayanıklılığı	Imported cold food, SARS-CoV-2, patojen kontrolü, COVID-19 sonrası dayanıklılık
6	12	Sürdürülebilir soğuk zincir tasarımı, izlenebilirlik ve sensör teknolojileri	Sürdürülebilir ağ tasarımı, paketleme, sıcaklık göstergeleri, 3PL, RFID sensörleri
7	12	Sıcaklık sapmaları, kalite kaybı ve gerçek zamanlı karar desteği	Time-temperature abuse, TTI, kalite kaybı, yeşil lojistik, sensör tabanlı izleme
8	11	IoT tabanlı çevresel izleme, anomali tespiti ve karar destek	Gerçek zamanlı anomali tespiti, çevresel parametre izleme, karar destek
9	8	Hasat sonrası kalite, raf ömrü ve meyve soğuk zinciri izlenebilirliği	Postharvest quality, shelf life, multi-sensor monitoring, fruit cold chains

Bibliyografik bağlantı yapısı, anahtar kelime ağında görülen kavramsal yönelimlerin yayın düzeyindeki karşılığını daha ayrıntılı biçimde ortaya koymaktadır. Birinci ve en büyük küme dijital ikiz, fizik tabanlı modelleme ve taze ürün kalite yönetimi etrafında yoğunlaşmaktadır. İkinci küme IoT/RFID tabanlı izleme, izlenebilirlik ve soğuk zincir risk yönetimini; üçüncü küme yapay zekâ, akıllı kalite kontrolü ve Endüstri 4.0 tabanlı dijitalleşmeyi temsil etmektedir. Dördüncü küme blokzincir, dijital izlenebilirlik ve sürdürülebilir soğuk zincir yönetimi üzerinde yoğunlaşırken, beşinci küme pandemi, gıda güvenliği ve soğuk zincir dayanıklılığı ekseninde ayrışmaktadır. Altıncı küme sürdürülebilir soğuk zincir tasarımı, izlenebilirlik ve sensör teknolojilerini; yedinci küme sıcaklık sapmaları, kalite kaybı ve gerçek zamanlı karar desteğini; sekizinci küme IoT tabanlı çevresel izleme, anomali tespiti ve karar desteğini; dokuzuncu küme ise hasat sonrası kalite, raf ömrü ve meyve soğuk zinciri izlenebilirliğini bir araya getirmektedir. Bu yapı, literatürde hem teknoloji odaklı hem de uygulama ve sorun odaklı uzmanlaşmış araştırma hatlarının birlikte geliştiğini göstermektedir.

Bu ağ yapısı, önceki literatürde öne çıkan izleme ve risk yönetimi çalışmalarının (Badia-Melis et al., 2018; Tsang et al., 2018) güncel literatürde daha çeşitli dijital teknoloji kümelerine ayrıldığını göstermektedir. Aynı zamanda Defraeye et al. (2021) tarafından vurgulanan dijital ikiz yaklaşımının ayrı ve büyük bir bibliyografik küme oluşturması, model tabanlı kalite tahmini ve karar desteğinin alan içinde belirgin bir araştırma hattına dönüştüğüne işaret etmektedir. Bununla birlikte bibliyometrik kümeler doğrudan işletme performansı veya sürdürülebilirlik etkisinin nedensel kanıtı değildir; literatürde birlikte gelişen araştırma yönelimlerini göstermektedir.

SONUÇ VE ÖNERİLER

Bu çalışma, gıda soğuk zinciri lojistiğinde dijitalleşme ve sürdürülebilirlik kesişimindeki 155 Web of Science yayınını 2010–2025 dönemi için bibliyometrik ve tematik olarak incelemiştir. Bulgular, alanın özellikle 2021 sonrasında hızla büyüdüğünü ve 2025 yılında 49 yayınla en yüksek yıllık üretim düzeyine ulaştığını göstermektedir. Cold chain kavramı alanın temel çekirdeğini korurken food waste, sustainability, Internet of Things, blockchain, artificial intelligence, machine learning ve digital twin gibi kavramlar giderek daha görünür hâle gelmiştir.

VOSviewer eş-oluşum analizi, en az 3 yayında görülen 35 yazar anahtar kelimesini 7 kümeye ayırmıştır. Bu kümeler; makine öğrenmesi destekli soğuk zincir kalite ve tazelik yönetimi, dijital dönüşüm-RFID ve bozulabilir ürün lojistiği, soğuk zincirde yapay zekâ-dijital ikiz ve model tabanlı yönetim, sürdürülebilirlik-izlenebilirlik ve ürün kalitesi, IoT tabanlı izleme ve raf ömrü yönetimi, gıda israfı-gıda güvencesi ve sıcaklık kontrollü tedarik zinciri ile gıda güvenliği-blokzincir ve pandemi dönemi sıcaklık izleme eksenlerinde ayrışmaktadır. Bibliyografik bağlantı analizinde ise 155 yayının 144'ü en büyük bağlı bileşeni oluşturmuş ve bu ağ 9 belge kümesine ayrılmıştır. Bu kümeler dijital ikiz ve fizik tabanlı modellemeden IoT/RFID, yapay zekâ, blokzincir, pandemi dayanıklılığı, sürdürülebilir tasarım, sıcaklık sapmaları, anomali tespiti ve hasat sonrası kaliteye uzanan uzmanlaşmış araştırma hatlarını ortaya koymaktadır. Sonuç olarak alan, tek bir dijital teknoloji etrafında değil, birbiriyle ilişkili çoklu teknoloji ve uygulama eksenleri üzerinden gelişmektedir.

Gelecek araştırmalar açısından üç yön öne çıkmaktadır. İlk olarak, dijital teknolojilerin teknik performansının enerji kullanımı, karbon etkisi, gıda kaybı ve kaynak verimliliği gibi ölçülebilir sürdürülebilirlik göstergeleriyle aynı araştırma tasarımında birlikte değerlendirilmesi, dijitalleşme-sürdürülebilirlik ilişkisinin daha somut biçimde sınanmasına katkı sağlayabilir. İkinci olarak, VOSviewer ağlarında belirginleşen yapay zekâ, dijital ikiz, IoT tabanlı anomali tespiti ve gerçek zamanlı karar destek uygulamalarının gerçek soğuk zincir ortamlarında farklı ürün grupları üzerinde uzun dönemli olarak test edilmesi önem taşımaktadır. Üçüncü olarak, yayın üretimindeki coğrafi yoğunlaşma dikkate alınarak farklı ülke, ürün ve tedarik zinciri yapılarını karşılaştıran çalışmaların artırılması, bulguların genellenebilirliğini güçlendirebilir.

Çalışmanın başlıca sınırlılığı veri kaynağının WoS Core Collection ile sınırlı olmasıdır. Sonuçlar kullanılan arama sorgusuna, WoS indeksleme uygulamalarına, içerik uygunluğu kararlarına ve thesaurus ile yapılan terim standardizasyonuna duyarlıdır. Küme adları VOSviewer tarafından otomatik üretilmemiş, küme üyelerinin ortak içerikleri temelinde araştırmacı tarafından yorumlanmıştır; bu nedenle farklı araştırmacılar aynı kümeleri farklı başlıklarla adlandırabilir. Bibliyografik bağlantı ağında 11 yayının en büyük bağlı bileşenin dışında kalması da ağ sonuçlarının tüm 155 yayın yerine 144 bağlantılı yayın üzerinden yorumlandığı anlamına gelmektedir. Ayrıca atıf değerleri 9 Eylül 2026 tarihindeki kümülatif durumu yansıtmaktadır ve yayın yaşı etkisinden bağımsız değildir. Gelecek çalışmalarda Scopus gibi ek veri tabanlarının kullanılması, bağımsız çift değerlendiriciyle içerik taraması yapılması ve farklı ağ/kümeleme ayarlarına ilişkin duyarlılık analizlerinin raporlanması tekrarlanabilirliği artırabilir.

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IŞIKLI KAVŞAKLARDA ADAPTİF SİNYALİZASYON SİSTEMİ

ADAPTIVE TRAFFIC SIGNAL SYSTEM AT TRAFFIC LIGHT CONTROLLED INTERSECTIONS

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ÖZET

Kentleşmenin hızlanması ve araç sayısındaki artış, şehir içi trafik yönetimini giderek karmaşık hale getirmektedir. Sabit zamanlı sinyalizasyon sistemleri değişken trafik koşullarına yanıt verememekte olup bu durum sıkışıklık, uzayan bekleme süreleri ve acil durum araçlarının müdahalesinde gecikmelere yol açmaktadır. Giresun Merkez ilçesinde belirlenen sekiz kollu bir dönel kavşak pilot bölge olarak seçilerek Adaptif Trafik Sinyalizasyon Sistemi geliştirilmiştir. Amaç, yüksek maliyetli merkezi altyapı sistemleri yerine, düşük maliyetli donanımlarla kavşak noktasında yerel karar alabilen maliyet etkin bir mimari kurmaktır. Sistemin kontrol birimi Raspberry Pi 4'tür. Birinci algılama aşamasında 38 kHz modülasyonlu kızılötesi (IR) sensör araç geçişlerini tespit etmekte olup iki sabit nokta arası geçiş süresinden araç hızı ve buna bağlı yoğunluk hesaplanmaktadır. İkinci aşamada Raspberry Pi HQ kameradan alınan görüntüler OpenCV ve YOLOv5 ile işlenerek araç sayımı ve acil durum aracı (ambulans, itfaiye, polis) sınıflandırması yapılmaktadır. IR verisi ile görsel çıkarımların birlikte değerlendirildiği bu hibrit yapı, çift sayım ve hatalı algılamaları azaltmaktadır. Karar algoritması, ölçülen yoğunluğa göre yeşil ışık süresini 10 ve 20 saniye aralığında dinamik olarak belirlemekte, acil durum aracı algılandığında ilgili yöne doğrudan öncelik verilmektedir. Ölçekli kavşak maketi üzerinde 40 araç geçişi ile yürütülen testlerde algılama doğruluğu %92,5, ortalama algılama süresi 0,2 saniye olarak ölçülmüştür. Sistemin saha ölçeğindeki davranışı, kavşağın gerçek geometrisi PTV Vissim uygulaması ortamına aktarılarak simülasyonla ayrıca sınanmıştır. Sabit zamanlı sisteme kıyasla ortalama bekleme süresi 52,3 saniyeden 37,6 saniyeye (%28,1), kavşaktan geçiş süresi 18,7 saniyeden 13,2 saniyeye (%29,4), ortalama kuyruk uzunluğu ise %32 oranında düşmüş; trafik akış verimliliğinde %25'e varan iyileşme elde edilmiştir. En belirgin avantaj acil durum araçlarında görülmüş, geçiş süresi 15,0 saniyeden 8,9 saniyeye (%40,7) inmiştir. Dur ve kalk hareketlerinin azalması, yakıt tüketimi ve karbon salımı açısından da dolaylı bir çevresel fayda sağlamaktadır. Bulgular, önerilen mimarinin bütçe ve altyapı kısıtı sorunu bulunan küçük ve orta ölçekli şehirler için uygulanabilir bir çözüm sunduğunu göstermektedir.

Anahtar kelimeler: Adaptif trafik sinyal kontrolü, Akıllı şehirler, Acil durum aracı geçiş önceliği, Hibrit algılama, PTV Vissim.

ABSTRACT

The rapid pace of urbanization and the increase in the number of vehicles have made urban traffic management increasingly complex. Fixed-time traffic signalization systems are unable to respond effectively to changing traffic conditions, resulting in congestion, increased waiting times, and delays in the intervention of emergency vehicles. An eight-arm roundabout located in Giresun city center was selected as the pilot area, and an Adaptive Traffic Signalization System was developed. The primary objective was to establish a cost-effective architecture capable of making local decisions at the intersection, using low-cost hardware instead of high-cost centralized infrastructure systems. The

control unit of the system is a Raspberry Pi 4. In the first detection stage, a 38 kHz modulated infrared (IR) sensor is used to detect vehicle passages, while vehicle speed and the corresponding traffic density are calculated based on the travel time between two fixed points. In the second stage, images acquired from a Raspberry Pi HQ Camera are processed using OpenCV and YOLOv5 to perform vehicle counting and emergency vehicle classification, including ambulances, fire trucks, and police vehicles. The hybrid architecture, in which IR data and visual inferences are jointly evaluated, reduces double counting and false detections. Based on the measured traffic density, the decision algorithm dynamically determines the green-light duration within a range of 10 to 20 seconds. When an emergency vehicle is detected, direct priority is given to the corresponding direction. In tests conducted on a scaled intersection model using 40 vehicle passages, a detection accuracy of 92.5% and an average detection time of 0.2 seconds were measured. The system's behavior at the field scale was additionally evaluated through simulation by transferring the actual geometry of the intersection into the PTV Vissim environment. Compared with the fixed-time system, the average waiting time decreased from 52.3 seconds to 37.6 seconds (28.1%), the intersection travel time decreased from 18.7 seconds to 13.2 seconds (29.4%), and the average queue length decreased by 32%. An improvement of up to 25% was achieved in traffic flow efficiency. The most significant advantage was observed for emergency vehicles, for which the travel time decreased from 15.0 seconds to 8.9 seconds (40.7%). The reduction in stop-and-go movements also provides indirect environmental benefits in terms of fuel consumption and carbon emissions. The findings indicate that the proposed architecture offers a feasible solution for small and medium-sized cities facing budgetary and infrastructure constraints.
Keywords: Adaptive traffic signal control, Smart cities, Emergency vehicle priority, Hybrid detection, PTV Vissim.

INTRODUCTION

The rapidly increasing number of vehicles and accelerating urbanization are making urban traffic management increasingly complex. Studies in the literature have shown that fixed-time signal control methods are unable to adapt to instantaneous fluctuations in traffic density (Güler, 2013; Pamuk, 2021). This results in unnecessary delays at intersections, increased fuel consumption, and reduced traffic safety (Chen, Ardila-Gomez, & Frame, 2017). Particularly in developing cities with challenging settlement patterns, such as Giresun, the inefficient management of green and red signal durations at intersections adversely affects the response times of emergency vehicles (ambulances, fire trucks, and police vehicles) (Nellore & Hancke, 2016).

In Intelligent Transportation Systems, traffic control requirements are defined at three levels: "Passive Control", "Right-of-Way Priority Assignment", and "Positive Control". This project aims to optimize the "Traffic Signalization System", which corresponds to the third level. Adaptive systems reported in the literature, such as SCATS (Australia; Sims & Dobinson, 1980) and SCOOT (United Kingdom; Hunt, Robertson, Bretherton, & Winton, 1981), remain inaccessible to small-scale local governments owing to their high costs. To address this gap in the literature, the present project was undertaken to develop a cost-effective and data-driven traffic management system that can be implemented by local governments, with a specific focus on the province of Giresun. The developed KAVŞAK360 system employs low-cost infrared (IR) sensors and image processing techniques instead of magnetic detectors. The primary objective of the study is to dynamically adjust the green-light durations of traffic signals according to the instantaneous vehicle count and to grant right-of-way priority to emergency vehicles while minimizing the need for human intervention in traffic management.

METHODOLOGY

In the developed adaptive signalization system, a Raspberry Pi 4, which offers low cost and high processing capacity, was employed as the hardware control unit. The system features a hybrid (combined) sensing architecture for collecting and processing environmental data.

First Detection Stage (Hardware Sensors): Infrared (IR) sensors modulated at 38 kHz were employed to detect vehicle passages at the intersection (Guerrero-Ibáñez, Zeadally, & Contreras-Castillo, 2018). The IR sensor module used, together with the Raspberry Pi 4 control unit to which it is connected, is shown in Figure 1. With the sensors positioned at two fixed points, the travel time of vehicles between

these points is measured, and vehicle speed and instantaneous traffic density are calculated from these data.

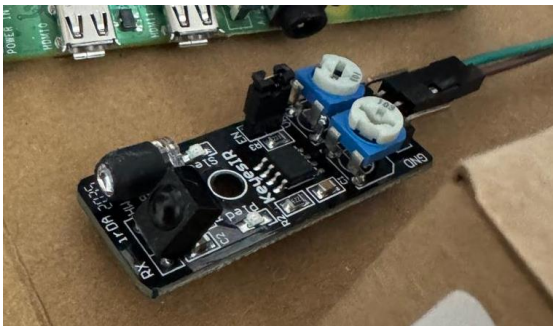


Figure 1. Infrared (IR) sensor module used for vehicle detection and the Raspberry Pi 4 control unit to which it is connected

Second Detection Stage (Image Processing): For visual detection, a Raspberry Pi HQ camera module equipped with a Sony IMX477 sensor was integrated into the system. The circuit schematic showing the connections among the IR sensor, the Raspberry Pi 4, and the 16×2 LCD module on which system information is displayed, together with the hardware setup of the camera, is presented in Figure 2. Real-time images captured by the camera are processed using the OpenCV library and the YOLOv5 deep learning model. YOLO-based detectors treat object detection as a single regression problem and predict bounding boxes and class probabilities directly from the entire image in a single network pass, which makes them well suited to real-time applications (Redmon, Divvala, Girshick, & Farhadi, 2016). Built on this approach, YOLOv5 uses an anchor-based prediction mechanism and consists of three main components: a CSPDarknet53 backbone that extracts features from the input image, a neck combining SPPF (Spatial Pyramid Pooling – Fast) and PANet (Path Aggregation Network) structures that aggregates features at different scales, and a YOLOv3-based head that generates the final bounding box and class predictions (Jocher, 2020; Ultralytics, n.d.). During training, the model is optimized with a composite loss function in which binary cross-entropy is used for the classification and objectness terms and Complete IoU (CIoU) is used for bounding box localization, while mosaic data augmentation improves generalization and reduces overfitting (Jocher, 2020). The lightweight variants of the model make it a practical choice for edge devices with limited computational capacity, such as the Raspberry Pi 4. At this stage, the system performs real-time vehicle counting while also detecting and classifying emergency vehicles (ambulances, fire trucks, and police vehicles) approaching the intersection. To enable the model to recognize emergency vehicles, the images in the dataset were annotated using the LabelImg tool under three classes (ambulance, fire truck, and police), and the vehicles were manually marked with bounding boxes (Figure 3). The YOLOv5 model was then trained on this dataset for 50 epochs; an excerpt from the training log, showing the box, objectness, and classification loss values together with the intermediate validation metrics, is presented in Figure 4.

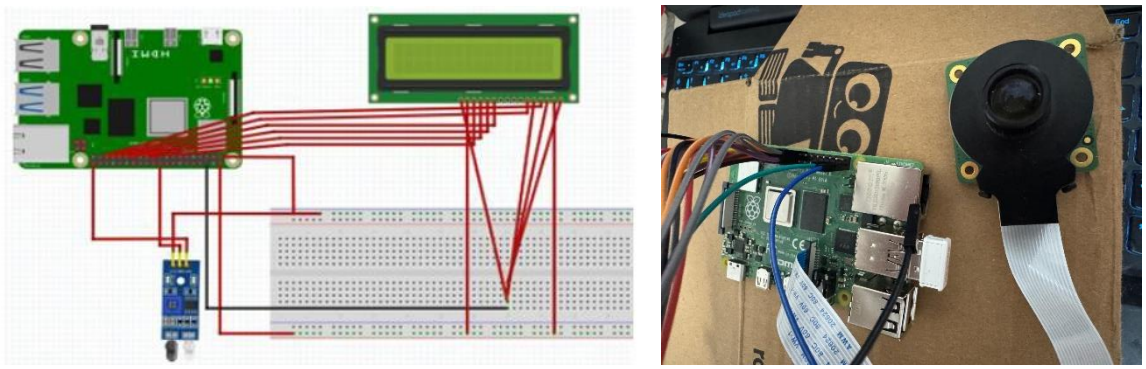


Figure 2. Raspberry Pi HQ Camera equipped with the Sony IMX477 sensor, connected to the Raspberry Pi 4 via a ribbon cable on the prototype (right); circuit schematic of the connections between the IR sensor, the Raspberry Pi 4, and the 16×2 LCD module via a breadboard, prepared in a Raspberry Pi simulator environment (left)

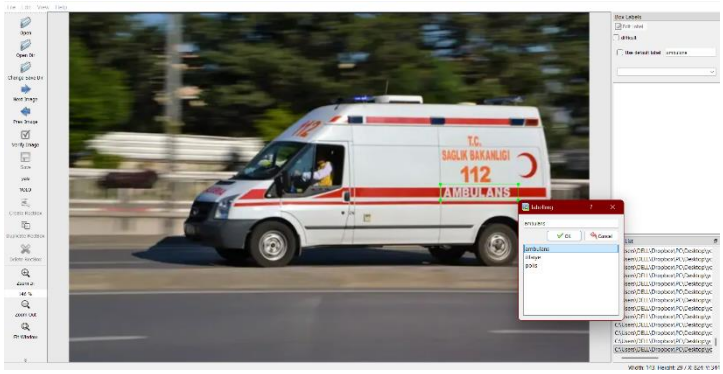


Figure 3. Annotation of an ambulance image with a manually defined bounding box in the LabelImg tool (classes: ambulance, fire truck, police)

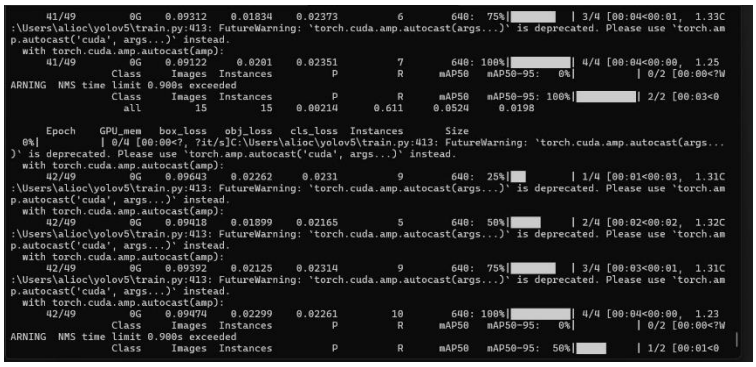


Figure 4. Excerpt from the training log of the YOLOv5 emergency vehicle detection model (epochs 41/49 and 42/49 of the 50-epoch training), showing the box, objectness, and classification loss values and the intermediate validation metrics

Hybrid Decision Algorithm: This hybrid structure, which jointly evaluates image processing (YOLOv5) and hardware-based (IR sensor) data, mitigates double counting and false detection problems that may arise from shadows or other environmental factors. The decision algorithm dynamically adjusts the green-light duration between 10 and 20 seconds based on the density data received from the sensor and the camera (Bayrakdar & Doğan, 2021). When the camera detects an emergency vehicle, the algorithm interrupts the normal flow and grants direct right-of-way priority to the corresponding direction (Nellore & Hancke, 2016). The operational workflow of the system, from data acquisition to signal phase assignment, is shown in Figure 5.

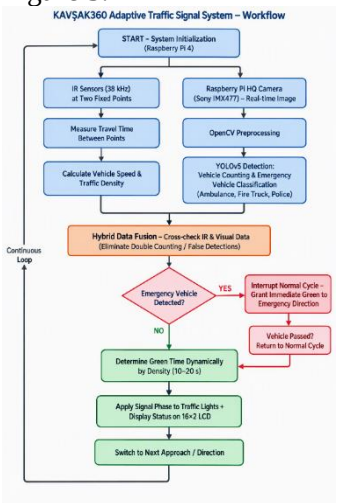


Figure 5. Operational workflow of the KAVŞAK360 system: parallel IR sensor- and camera-based data acquisition, hybrid data fusion, emergency vehicle priority, and density-based green time assignment (10–20 s)

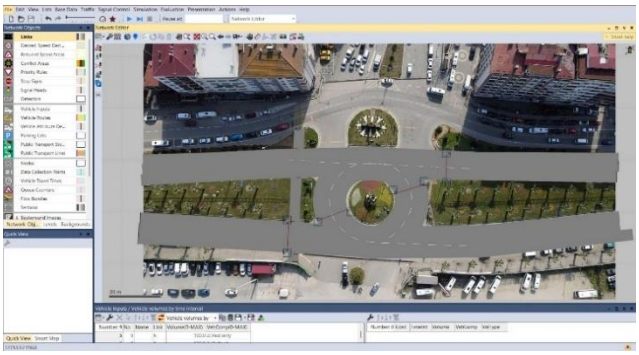


Figure 6. Network model of the pilot roundabout created on the aerial image of the intersection in the PTV Vissim environment

Simulation and Modeling: To safely analyze the behavior of the system at the field scale, the actual geometry of the pilot intersection was transferred to the PTV Vissim traffic simulation environment (PTV Group, 2023), and the algorithms were also tested in this virtual environment. The network model of the pilot intersection created in PTV Vissim is presented in Figure 6.

RESEARCH FINDINGS AND DISCUSSION

The performance of the developed system was first evaluated on a physical scaled intersection model. In the test involving 40 vehicle passages on the model, the detection accuracy, determined by taking into account both detection success and the response delay of the system, was 92.5%, while the average detection time was a remarkably low 0.2 seconds. The validation score (mAP@0.5) of the YOLOv5 model used for emergency vehicle classification was 89.9%. The results of the single-vehicle, sequential-vehicle, and emergency vehicle scenarios examined in the model tests are presented in Table 1. Although all vehicles were detected in these scenarios, the accuracy values in the table were derived not from the limited scenario-level trials but from the overall reliability of the corresponding detection module: the 92.5% obtained in the 40-passage test was used for the IR sensor-based scenarios, whereas the 89.9% mAP@0.5 value of the YOLOv5 model was used for the emergency vehicle scenario. In the PTV Vissim simulations reflecting field conditions, the proposed system exhibited a clear advantage over fixed-time signalization. The average waiting time at the intersection decreased from 52.3 seconds to 37.6 seconds, an improvement of 28.1%, while the transit time of vehicles through the intersection decreased from 18.7 seconds to 13.2 seconds, a reduction of 29.4%.

A 32% reduction was observed in the average queue lengths on the intersection approaches.

As a combined effect of these improvements, an increase of up to 25% in overall traffic flow efficiency was achieved.

The most critical benefit of the system emerged in the passage of emergency vehicles. Owing to the adaptive prioritization algorithm, the travel time of these vehicles in the simulation decreased from 15.0 seconds to 8.9 seconds, a notable reduction of 40.7%. Furthermore, the reduction in waiting times and in stop-and-go movements is expected to yield indirect environmental benefits in terms of fuel consumption and carbon emissions.

Table 1. Experimental scenarios and system responses on the scaled intersection model

Scenario	Total Vehicles (count)	Correct Detections (count)	Accuracy (%)	Avg. Delay (s)	Green Time (s)	Emergency Response (s)
1. Single-vehicle transit	4	4	92.5	3.6	10	-
2. Sequential transit (4 vehicles)	4	4	92.5	3.6	20	-
3. Emergency vehicle detection (Ambulance, Fire Truck, Police)	3	3	89.9	1.5	Immediate	2.6

Note. The total and correct detection counts represent the successful trials in the physical prototype tests.

The Accuracy (%) column does not represent the simple ratio of correctly detected vehicles to the total number of vehicles; rather, it reflects the overall reliability of the corresponding detection module (for the IR sensor-based scenarios, the result of the 40-passage test, which also accounts for response delay; for the emergency vehicle scenario, the YOLOv5 mAP@0.5 value). The Avg. Delay (s) column indicates the average system delay in the corresponding scenario, which differs from the 0.2-second detection time reported in the text, whereas the Emergency Response (s) column shows the time elapsed on the model from the detection of the emergency vehicle to the activation of the green light. This duration is a different measurement from the 8.9-second emergency vehicle travel time obtained in the PTV Vissim simulation.

CONCLUSION

In this study, an intelligent and adaptive traffic signalization system was designed by combining cost-effective hardware with hybrid sensing algorithms (infrared sensors and deep learning-assisted image processing). The model tests and PTV Vissim simulations demonstrated that the developed architecture shortens waiting times, reduces queue lengths, and safely grants right-of-way priority to emergency vehicles. The findings indicate that the proposed system offers a feasible, practical, and effective solution to traffic problems, particularly in small and medium-sized cities with budgetary and infrastructure constraints.

ACKNOWLEDGEMENTS

This study was supported under the TÜBİTAK 2209-A University Students Research Projects Support Program and was selected as a finalist project in the TEKNOFEST 2242 competition.

RECOMMENDATIONS

Hardware and Algorithm Upgrades: To improve the real-time detection performance for ambulances and other emergency vehicles, it is recommended that the current image processing infrastructure be upgraded to the YOLOv8 architecture. In addition, supporting the system with hardware of higher processing capacity, such as the NVIDIA Jetson Orin NX, to enable more efficient data processing would maximize the speed and accuracy of the decision mechanism.

Sensor Improvements: To minimize the impact of environmental factors such as heavy rainfall and fog on infrared (IR) sensors at wide, multi-lane intersections, it is recommended that the system be extended to operate in integration with LIDAR or radar technologies.

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MATHEMATICAL MODELING OF THE BLACK SEA ANCHOVY-PLANKTON SYSTEM: EQUILIBRIUM AND STABILITY ANALYSIS

KARADENİZ HAMSİSİ-PLANKTON SİSTEMİNİN MATEMATİKSEL MODELLENMESİ: DENGE VE KARARLILIK ANALİZİ

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Abstract
This study presents a low-dimensional, stage-structured mathematical model of plankton-anchovy interactions in the Black Sea. The aim is to characterize biologically feasible equilibria and determine their local stability while accounting for two anchovy life stages. The system is formulated as a set of four autonomous ordinary differential equations describing phytoplankton P(t), zooplankton Z(t), pre-recruit anchovy biomass L(t), and adult anchovy biomass A(t). Separating the two anchovy compartments allows life-stage transitions to be represented explicitly within the plankton-fish system. Phytoplankton dynamics follow logistic growth, whereas trophic interactions are represented by Holling Type II functional responses. Natural losses, transitions between anchovy life stages, and fishing mortality are included. Extinction, boundary, and positive coexistence equilibria are determined, and the conditions for their biological feasibility are examined. These equilibrium categories distinguish the absence of all components, the presence of only a subset of components, and the coexistence of all four components. Local stability is evaluated using the Jacobian matrix and its eigenvalues. Under the reference parameter set, extinction and boundary equilibria are unstable, whereas the positive coexistence equilibrium is locally asymptotically stable. All eigenvalues at this equilibrium have negative real parts, indicating that small perturbations around coexistence decay over time. Numerical simulations and phase trajectories are consistent with convergence toward the positive equilibrium. Together, these results characterize locally stable coexistence under the reference conditions, with all four biological components present and small perturbations followed by a return toward the positive equilibrium. Future work will incorporate maturation delay and examine delay-dependent stability changes, possible oscillations, and interactions with annual seasonal forcing.
Keywords: Black Sea anchovy, plankton, stage-structured model, stability analysis, ordinary differential equations.

Özet
Bu çalışmada, Karadeniz'deki plankton-hamsi etkileşimlerini incelemek amacıyla düşük boyutlu ve safha yapılı bir matematiksel model sunulmuştur. Çalışmanın amacı, hamsinin iki yaşam safhasını dikkate alarak biyolojik açıdan anlamlı denge noktalarını belirlemek ve bu dengelerin yerel kararlılığını incelemektir. Sistem; fitoplankton P(t), zooplankton Z(t), stoğa katılım öncesi hamsi biyokütlesi L(t) ve ergin hamsi biyokütlesi A(t) olmak üzere dört durum değişkenini içeren otonom bir adi diferansiyel denklem sistemi olarak kurulmuştur. Hamsinin iki ayrı biyokütle bileşeniyle temsil edilmesi, yaşam safhaları arasındaki geçişlerin plankton-balık sistemi içerisinde açık biçimde ele alınmasını sağlamaktadır. Fitoplankton dinamiği lojistik büyümeyle, trofik etkileşimler ise Holling Tip II fonksiyonel tepkileriyle ifade edilmiştir. Doğal kayıplar, hamsinin yaşam safhaları arasındaki geçiş ve balıkçılık kaynaklı ölüm hızı modele dâhil edilmiştir. Modelin yokluk, sınır ve pozitif birlikte yaşama denge noktaları belirlenmiş, bu dengelerin biyolojik anlamlılık koşulları incelenmiştir. Bu denge sınıfları sırasıyla bütün bileşenlerin yokluğunu, biyolojik bileşenlerin yalnızca bir bölümünün varlığını ve dört bileşenin tamamının birlikte bulunduğu durumu temsil etmektedir. Yerel kararlılık analizi Jacobian matrisi ve özdeğerler kullanılarak yapılmıştır. Referans parametre setinde yokluk ve sınır dengelerinin kararsız, pozitif birlikte yaşama dengesinin ise yerel asimptotik kararlı olduğu belirlenmiştir. Bu dengedeki bütün özdeğerlerin gerçek kısımlarının negatif olması, denge çevresindeki

küçük pertürbasyonların zamanla sönümlendiğini göstermektedir. Sayısal benzetimler ve faz yörüngeleri de çözümlerin pozitif dengeye yönelmesiyle uyumludur. Bu sonuçlar, referans koşullarda dört biyolojik bileşenin birlikte bulunduğu ve küçük pertürbasyonlardan sonra pozitif dengeye dönme eğilimi gösteren yerel olarak kararlı bir birlikte yaşama durumunu ortaya koymaktadır. Gelecek çalışmalarda modele olgunlaşma gecikmesi eklenerek gecikmeye bağlı kararlılık değişimleri, olası salınımlar ve yıllık mevsimsel zorlamayla etkileşim incelenecektir.

Anahtar kelimeler: Karadeniz hamsisi, plankton, safha yapılı model, kararlılık analizi, adi diferansiyel denklemler.

INCREMENTAL DISCRIMINATORY VALUE OF SOCIOECONOMIC AND HEALTHCARE-ACCESS INFORMATION FOR DOCUMENTED IRON-CHELATION ADHERENCE IN THALASSEMIA

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ABSTRACT
This study evaluated whether socioeconomic and healthcare-access information provides incremental discriminatory information for documented iron-chelation adherence beyond demographic, clinical, and treatment characteristics among actively chelated patients with thalassemia. The open Bangladesh Thalassemia Dataset included 617 patients. After excluding 152 patients with Chelation_Adherence coded as N/A and 18 records with documented adherence despite no active chelation therapy, the prespecified analytic cohort comprised 447 patients, all with Thalassemia Major or Intermedia and receiving active chelation therapy. Chelation adherence was dichotomized as high (n=185) versus medium/low (n=262). The reference feature set included demographic, clinical, laboratory, transfusion, and chelation-regimen variables, whereas the extended set additionally included residence, education, monthly household income, and travel time to hospital. L2-regularized Logistic Regression was the prespecified primary model; RBF-SVM, Random Forest, and XGBoost were evaluated as robustness models. Performance was assessed using repeated nested stratified cross-validation with identical saved partitions for reference and extended models. Uncertainty in incremental performance was quantified using 10,000 paired patient-level bootstrap resamples of aggregated out-of-fold predictions. In the primary Logistic Regression analysis, ROC-AUC increased from 0.9514 to 0.9647, yielding a Delta AUC of 0.0133 (95% CI 0.0017 to 0.0259). Brier score decreased from 0.0847 to 0.0620, with a Delta Brier of -0.0227 (95% CI -0.0349 to -0.0113). Incremental AUC gains were not consistently reproduced across the nonlinear robustness models. The prespecified raw travel-time sensitivity analysis produced a similar direction and magnitude to the primary analysis. These findings indicate that socioeconomic and healthcare-access information provided modest incremental discriminatory information in the prespecified Logistic Regression framework, but that the incremental AUC gain was not consistent across model classes and should not be interpreted causally or as evidence of clinical utility.
Keywords: Thalassemia, iron-chelation adherence, socioeconomic factors, healthcare access, incremental discrimination

INTRODUCTION
Thalassemia comprises a heterogeneous group of inherited hemoglobin disorders characterized by reduced or absent globin-chain synthesis. In patients requiring regular red-cell transfusions, progressive iron accumulation is expected because the human body lacks an effective physiological mechanism for eliminating the transfusional iron load. Without adequate control, iron overload may contribute to cardiac, hepatic, endocrine, and other complications. Iron-chelation therapy is therefore a central component of long-term management, and current Thalassaemia International Federation guidance emphasizes the importance of appropriate and sustained chelation therapy in transfusion-dependent thalassemia (Musallam et al., 2025).
Maintaining adherence to long-term iron-chelation therapy remains challenging. Systematic reviews in adults and younger populations have reported substantial heterogeneity in adherence estimates and in the methods used to assess adherence, including self-report, pill counts, prescription-refill information, and clinician assessment (Locke, Reddy, & Badawy, 2022; Reddy, Locke, & Badawy, 2022). More recent literature treats adherence as a multifactorial process associated with patient-, medication-, and

healthcare-system-level factors, including treatment burden, adverse effects, financial constraints, and access to specialist care (Wang, Muttar, & Badawy, 2025).

Socioeconomic and healthcare-access factors may be particularly relevant in resource-constrained settings. Among Malaysian adolescents with transfusion-dependent thalassemia, monthly household income was associated with iron-chelation adherence (Mohamed, Abdul Rahman, Masra, & Abdul Latiff, 2022). In Pakistani children with β-thalassemia major, travel time to the treatment center and annual transfusion burden were identified as predictors of non-adherence (Kanwal, Ahmad, Tariq, & Gul-e-Rehan, 2022). A 2026 multicenter study from Punjab using the Treatment Adherence Scale also reported adherence associations with age, residence, chelation regimen, and serum ferritin (Muneeb et al., 2026). Qualitative and Bangladesh-based studies have identified travel distance and financial constraints as barriers to treatment adherence (Emami Zeydi, Karimi Moonaghi, & Heydari, 2017; Barua et al., 2021). More broadly, a recent review of thalassemia care in Bangladesh describes persistent limitations in treatment infrastructure, access to iron chelation, and multidisciplinary care (Hossain, Islam, Akhter, & Al Mossabbir, 2025). A recent study from Palestine also reported associations between adherence and socioeconomic or healthcare-service characteristics (Al Zabadi, Ieran, & Taha, 2025).

Most previous studies have examined associations between individual socioeconomic, behavioral, or healthcare-related factors and treatment adherence, or whether such factors are perceived as treatment barriers. A related but distinct question is whether socioeconomic and healthcare-access information provides additional discriminatory information when demographic, clinical, laboratory, transfusion, and treatment characteristics are already available. The recently published Bangladesh Thalassemia Dataset brings these domains together in the same cohort, including residence, education, monthly household income, travel time to hospital, laboratory findings, treatment characteristics, and documented chelation adherence (Ayon et al., 2025a, 2025b).

Accordingly, this study evaluated whether adding a prespecified socioeconomic and healthcare-access variable block to a demographic/clinical/treatment reference model provides incremental discriminatory information for documented iron-chelation adherence. L2-regularized Logistic Regression was prespecified as the primary analytical framework. RBF-SVM, Random Forest, and XGBoost were used to assess whether the direction of incremental performance was retained across nonlinear model classes. The analysis was designed to quantify incremental discrimination rather than to establish causal effects or select a prediction algorithm for clinical use.

MATERIAL AND METHODS

2.1. Study Design and Data Source

This study was conducted as a secondary cross-sectional analysis of the publicly available Bangladesh Thalassemia Dataset (Ayon et al., 2025a). Data were collected from 617 patients with thalassemia attending LABAID LTD. (Diagnostic), Pabna, Bangladesh, between March and June 2025 through face-to-face interviews, medical records, and hospital laboratory data (Ayon et al., 2025b). The published data description covers demographic, socioeconomic, clinical, laboratory, treatment, and mental-health information. The repository describes 23 study variables. The downloaded CSV used in the present analysis contained 24 columns when the patient-specific Patient_ID identifier was included. The associated data article reports that the data were de-identified, informed consent was obtained during the original data collection, and the study protocol was reviewed and approved by the medical and administrative authorities at LABAID LTD. (Diagnostic), Pabna, Bangladesh (Ayon et al., 2025b).

The analytic cohort was defined before predictive modeling. Records with Chelation_Adherence coded as N/A (n=152) were excluded. An additional 18 records contained documented High, Medium, or Low adherence despite no active iron-chelation therapy and were excluded as treatment-adherence inconsistencies. No other exclusions were applied, and the final analytic cohort comprised 447 patients. All patients in the final cohort had Thalassemia Major or Intermedia and were receiving an active DFP, DFX, or DFX + DFP chelation regimen.

Documented chelation adherence was prespecified as a binary outcome. High adherence was coded as the positive class (n=185), whereas Medium (n=234) and Low (n=28) adherence were combined as the negative class (n=262). The source data article identifies Low, Medium, High, and N/A as the available adherence categories but does not report the operational criteria, threshold values, recall interval, or a validated adherence instrument used to assign Low, Medium, and High categories (Ayon et al., 2025b).

The endpoint is therefore referred to throughout this study as documented adherence. Cohort selection is illustrated in Figure 1.

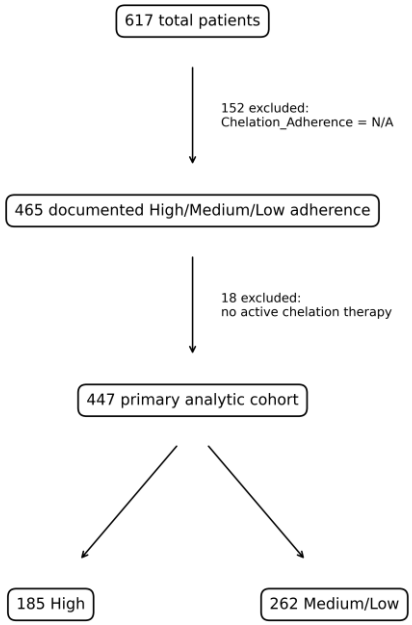


Figure 1. Study cohort flow. Flow from 617 records to the 447-patient primary analytic cohort and the distribution of the binary adherence outcome.

2.2. Reference and Extended Predictor Sets

Two prespecified model-variable sets were compared. The demographic/clinical/treatment reference set consisted of 15 variables: current age, gender, age at diagnosis, thalassemia type, splenectomy status, pre-transfusion hemoglobin, serum ferritin, mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH), red cell distribution width (RDW), reticulocyte count, fetal hemoglobin percentage (HbF), transfusion frequency, iron-chelation regimen, and body mass index (BMI).

The extended set included all reference variables plus four socioeconomic and healthcare-access variables: residence type, education level, monthly household income, and travel time to hospital. Monthly household income is reported in Bangladeshi Taka in the original data description (Ayon et al., 2025b). Patient_ID and the adherence outcome were not used as model inputs. School/Work Impact, Mental Health Status, and Self-Reported Comorbidities were also excluded from both prespecified variable sets. No subsequent outcome-driven feature selection was performed.

2.3. Data Preprocessing

Preprocessing rules were specified before predictive modeling and were applied separately within each training partition. Only leading and trailing whitespace was removed from categorical values, without changing their semantic content. Monthly household income was converted to numeric form by removing comma grouping separators; no income categorization or thresholding was performed.

Categorical variables were treated as nominal and encoded using one-hot encoding with handle_unknown="ignore" and min_frequency=5. Categories and infrequent-category groupings were learned exclusively from the corresponding training partition. Education level was not assigned an ordinal numerical code.

No imputation was performed because there were no missing data among the variables defined for the reference and extended sets before modeling. No observation was excluded or modified according to numerical magnitude. No capping or winsorization was performed.

For Logistic Regression and RBF-SVM, numerical variables were standardized using parameters estimated exclusively from the corresponding training data. In the primary analysis, travel time to hospital was transformed using log1p before standardization. Numerical variables were not standardized

for Random Forest or XGBoost, although the prespecified log1p transformation of travel time was retained. No oversampling, undersampling, SMOTE, sample weighting, or class weighting was used.

2.4. Primary Logistic Regression Analysis

L2-regularized Logistic Regression was prespecified as the primary model. Models were fitted using the lbfgs solver, class_weight=None, and a maximum of 5,000 iterations. The regularization parameter C was selected from the prespecified grid {0.01, 0.1, 1, 10, 100}.

Model development and evaluation were performed using repeated nested stratified cross-validation. Nested cross-validation separates hyperparameter selection from outer performance assessment and can reduce optimistic bias when model selection and error estimation are performed at the same cross-validation level (Varma & Simon, 2006).

The outer cross-validation loop comprised 25 outer test folds generated by repeating five-fold stratified cross-validation five times. To support reproducibility, the random-number-generator seed used to generate the outer cross-validation partitions was fixed at 20260907. Inner cross-validation partitions were generated using seeds deterministically derived from this base value. Within each outer training partition, hyperparameter selection was performed using five-fold stratified inner cross-validation. Mean inner-fold ROC-AUC was used as the selection criterion; in the event of an exact tie, the smaller C value was selected.

Reference and extended models used identical saved patient-level inner and outer data partitions. All learned preprocessing steps and model fitting were performed exclusively within the corresponding training partitions. After hyperparameter selection, the selected modeling pipeline was refitted on the complete outer training partition and applied to the previously unused outer test partition.

In each of the five repeats, every patient appeared in exactly one outer test fold and received one out-of-fold probability estimate from each of the models fitted with the reference and extended variable sets. Thus, after five repeats, each patient had five out-of-fold probability estimates from each model. Before calculation of the final performance measures and bootstrap analyses, these five probabilities were averaged to obtain one aggregated probability estimate per patient and per model.

2.5. Performance Measures and Incremental Value

ROC-AUC was prespecified as the primary performance measure. ROC-AUC summarizes discrimination across possible classification thresholds (Fawcett, 2006; Steyerberg et al., 2010). Secondary measures included the Brier score, balanced accuracy, F1 score, sensitivity, and specificity. The Brier score measures probabilistic prediction error and should not be interpreted as a calibration measure alone (Brier, 1950; Steyerberg et al., 2010). Threshold-based metrics were calculated using a fixed probability threshold of 0.50, and no threshold optimization was performed.

The primary incremental-value measure was defined as $\Delta AUC = AUC_{extended} - AUC_{reference}$. The corresponding change in Brier score was defined as $\Delta Brier = Brier_{extended} - Brier_{reference}$. Thus, positive ΔAUC indicates greater discrimination in the extended model, whereas negative $\Delta Brier$ indicates lower probabilistic prediction error.

Uncertainty was quantified using 10,000 paired patient-level bootstrap resamples. Reference and extended predictions remained paired by Patient_ID within each resample. Bootstrap sampling was performed after the five out-of-fold predictions for each patient had been aggregated into a single probability. Percentile-based 95% confidence intervals were calculated for AUC, Brier score, ΔAUC, and $\Delta Brier$. These intervals are conditional on the saved aggregated out-of-fold predictions and do not incorporate uncertainty arising from regeneration of cross-validation partitions, hyperparameter reselection, and complete model refitting.

2.6. Robustness Analyses

Radial-basis-function support vector machine (RBF-SVM), Random Forest, and XGBoost were evaluated as prespecified nonlinear robustness models. Support-vector machines construct decision boundaries in transformed feature spaces (Cortes & Vapnik, 1995), Random Forest combines ensembles of randomized decision trees (Breiman, 2001), and XGBoost implements gradient-boosted decision trees in a scalable boosting framework (Chen & Guestrin, 2016). These models were used to evaluate whether the direction and approximate magnitude of the incremental contribution from the socioeconomic/access variable block were retained across different model classes; they were not used to select an algorithm to replace the primary Logistic Regression model.

All robustness models used the same saved inner and outer Patient_ID partitions as the primary analysis. For RBF-SVM, C was selected from {0.1, 1, 10, 100} and gamma from {scale, 0.01, 0.1}. For Random Forest, 500 trees and max_features="sqrt" were used, with max_depth selected from {None, 5, 10} and min_samples_leaf from {1, 5, 10}. For XGBoost, objective="binary:logistic", subsample=0.8, colsample_bytree=0.8, and scale_pos_weight=1 were fixed; max_depth was selected from {2, 4}, learning rate from {0.03, 0.1}, and number of estimators from {200, 500}. Selection within the prespecified hyperparameter grids was based on mean inner ROC-AUC. RBF-SVM probability estimates were generated with SVC probability estimation enabled during training, with outer test rows excluded from probability fitting. For the robustness grids, exact ties in mean inner ROC-AUC retained the first configuration in prespecified grid order, and stochastic estimators used deterministic fold-specific seeds.

The patient-level prediction aggregation procedure, fixed 0.50 threshold, performance measures, and paired bootstrap approach used in the primary analysis were also applied to the robustness models.

2.7. Sensitivity Analysis

A prespecified sensitivity analysis evaluated whether the primary Logistic Regression finding was sensitive to the transformation applied to travel time to hospital. Only the extended Logistic Regression model was refitted, with the recorded raw travel-time values used directly before training-fitted standardization instead of the log1p transformation. Frozen reference predictions from the primary analysis remained unchanged.

All 447 patients and all recorded travel-time values were retained. No observation was deleted, capped, winsorized, or otherwise modified. The same saved nested cross-validation partitions, Logistic Regression features, C grid, performance measures, and paired patient-level bootstrap approach were used.

2.8. Software and Reproducibility

Analyses were performed using Python 3.14.3, pandas 3.0.2, NumPy 2.4.4, SciPy 1.17.1, scikit-learn 1.8.0, and XGBoost 3.2.0. Scikit-learn provided the machine-learning implementations and preprocessing/modeling pipeline infrastructure used in the primary and robustness analyses (Pedregosa et al., 2011), while XGBoost was implemented using its dedicated package (Chen & Guestrin, 2016). Fixed random-number-generator seeds and saved Patient_ID-level partition manifests were used to support reproducibility. Data auditing, preprocessing validation, primary modeling, robustness analyses, sensitivity analyses, and publication-output preparation were carried out in separate Python files. Integrity checks in subsequent stages verified that previously frozen analysis outputs had not been modified.

RESULTS AND DISCUSSION

3.1. Analytic Cohort Characteristics

The final analytic cohort comprised 447 patients. High documented chelation adherence was recorded for 185 patients (41.4%), Medium adherence for 234 (52.3%), and Low adherence for 28 (6.3%). Mean age was 23.0 ± 10.4 years, and 234 patients (52.3%) were male. Thalassemia Intermedia accounted for 290 patients (64.9%), whereas 157 (35.1%) had Thalassemia Major. Splenectomy had been performed in 258 patients (57.7%).

Among active chelation regimens, 191 patients (42.7%) received deferiprone (DFP), 203 (45.4%) received deferasirox (DFX), and 53 (11.9%) received combined DFX + DFP therapy. Median serum ferritin was 950 ng/mL [Q1-Q3: 910-3,475], and median transfusion frequency was 1.60 units/month [1.25-4.65].

Regarding socioeconomic and access characteristics, 212 patients (47.4%) resided in rural areas and 235 (52.6%) in urban areas. Median monthly household income was 25,000 Bangladeshi Taka [20,000-30,000], and median travel time to hospital was 45 minutes [22-70]. Detailed cohort characteristics are presented in Table 1.

Table 1. Selected characteristics of the primary analytic cohort (N=447).

Characteristic	Value
Chelation adherence	
High	185 (41.4%)
Medium	234 (52.3%)
Low	28 (6.3%)
Age, years	23.0 ± 10.4
Gender	
Female	213 (47.7%)
Male	234 (52.3%)
Age at diagnosis, years	4.84 ± 1.91
Thalassemia type	
Intermedia	290 (64.9%)
Major	157 (35.1%)
Splenectomy status	
No	189 (42.3%)
Yes	258 (57.7%)
Pre-transfusion hemoglobin, g/dL	9.14 ± 2.42
Serum ferritin, ng/mL	950 [910-3,475]
Transfusion frequency, units/month	1.60 [1.25-4.65]
Active chelation regimen	
DFP	191 (42.7%)
DFX	203 (45.4%)
DFX + DFP	53 (11.9%)
Body mass index, kg/m²	17.9 ± 4.4
Residence	
Rural	212 (47.4%)
Urban	235 (52.6%)
Education level	
None	11 (2.5%)
Preschool	3 (0.7%)
Primary	53 (11.9%)
Secondary	184 (41.2%)
Graduate	195 (43.6%)
Postgraduate	1 (0.2%)
Monthly household income, BDT	25,000 [20,000-30,000]
Travel time to hospital, min	45 [22-70]

Values are n (%), mean ± SD, or median [Q1-Q3], as appropriate. BDT: Bangladeshi Taka.

3.2. Primary Incremental-Value Analysis

In the prespecified primary Logistic Regression analysis, the demographic/clinical/treatment reference model achieved a ROC-AUC of 0.9514, whereas the extended model incorporating socioeconomic and healthcare-access variables achieved a ROC-AUC of 0.9647. The resulting ΔAUC was 0.0133, with a paired patient-level bootstrap 95% confidence interval of 0.0017-0.0259.

The Brier score decreased from 0.0847 in the reference model to 0.0620 in the extended model, corresponding to ΔBrier -0.0227 (95% CI -0.0349 to -0.0113). At the fixed threshold of 0.50, balanced accuracy increased from 0.8739 to 0.9319, F1 score from 0.8525 to 0.9210, sensitivity from 0.8432 to 0.9135, and specificity from 0.9046 to 0.9504.

Thus, despite the already high discrimination of the reference model, adding the prespecified socioeconomic/access variable block produced a modest but measurable increase in discrimination within the primary Logistic Regression framework. Although the paired bootstrap confidence interval for ΔAUC did not include zero, this interval is conditional on the aggregated out-of-fold predictions and

does not represent uncertainty arising from complete repetition of the entire modeling procedure. Primary results are summarized in Table 2.

Table 2. Primary Logistic Regression performance and incremental value.

Measure	Reference	Extended	Extended - Reference
ROC-AUC	0.9514 (0.9319-0.9689)	0.9647 (0.9462-0.9806)	+0.0133 (0.0017-0.0259)
Brier score	0.0847 (0.0677-0.1027)	0.0620 (0.0468-0.0787)	-0.0227 (-0.0349 to -0.0113)
Balanced accuracy	0.8739	0.9319	+0.0580
F1 score	0.8525	0.9210	+0.0685
Sensitivity	0.8432	0.9135	+0.0703
Specificity	0.9046	0.9504	+0.0458

AUC and Brier values are shown with 95% confidence intervals where applicable. Differences are extended minus reference. ΔAUC and ΔBrier intervals are paired patient-level bootstrap intervals.

3.3. Robustness Across Model Classes

The incremental AUC finding observed in the primary Logistic Regression analysis was not consistently reproduced across the nonlinear robustness models. RBF-SVM produced reference and extended AUCs of 0.9748 and 0.9748, respectively, yielding ΔAUC 0.0000 (95% CI -0.0076 to 0.0081). Random Forest yielded AUCs of 0.9870 and 0.9887, corresponding to ΔAUC 0.0016 (95% CI -0.0004 to 0.0040). XGBoost yielded reference and extended AUCs of 0.9829 and 0.9809, respectively, with ΔAUC -0.0020 (95% CI -0.0079 to 0.0037).

Accordingly, the ΔAUC confidence intervals included zero for all three nonlinear models, and the direction of the point estimates differed across model classes. Random Forest showed a very small positive ΔAUC, RBF-SVM had a ΔAUC point estimate of 0.0000 with no observed AUC change, and XGBoost showed a small negative ΔAUC. These findings do not support a model-class-independent and consistent incremental AUC contribution from the socioeconomic/access block. Model-specific ΔAUC estimates and paired confidence intervals are shown in Figure 2.

Brier-score point estimates changed in favor of the extended model, that is, toward lower probabilistic prediction error, for all three robustness models. ΔBrier was -0.0049 for RBF-SVM, -0.0024 for Random Forest, and -0.0014 for XGBoost. However, the 95% confidence intervals for ΔBrier included zero for all three robustness models. Thus, although the direction of the Brier-score changes was consistent across models, lower probabilistic prediction error was not clearly supported by the uncertainty intervals in any of the robustness models.

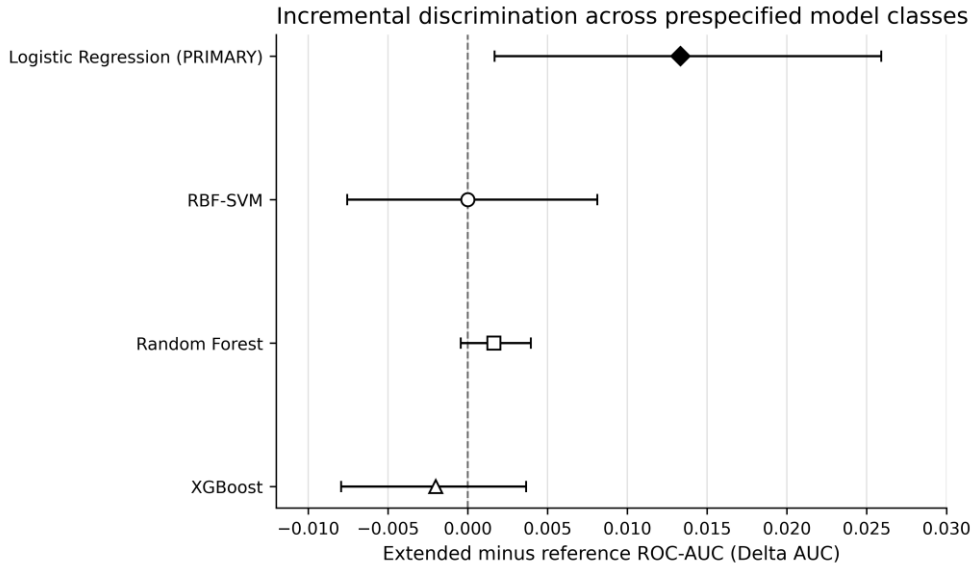


Figure 2. Incremental ROC-AUC across prespecified model classes. Extended-minus-reference ROC-AUC differences are shown with paired patient-level bootstrap 95% confidence intervals. Logistic

Regression is the primary analysis; the other models are robustness analyses. The vertical dashed line indicates ΔAUC = 0.

3.4. Travel-Time Sensitivity Analysis

The prespecified raw travel-time sensitivity analysis produced results similar to those from the primary log1p specification. When travel time to hospital was entered in raw minutes, the extended Logistic Regression model achieved an AUC of 0.9634. The reference model was not refitted, and the reference predictions from the primary analysis were retained unchanged. Relative to the reference model, ΔAUC was 0.0120 (95% CI 0.0002 to 0.0247). The Brier score was 0.0640, with ΔBrier -0.0207 (95% CI -0.0330 to -0.0091).

Compared with the primary log1p specification, the extended model using raw travel time had an AUC that was 0.0013 lower and a Brier score that was 0.0021 higher. All five repeat-specific ΔAUC point estimates remained positive. These findings indicate that the direction of the incremental AUC finding observed in the primary Logistic Regression analysis was preserved and that its magnitude was affected only to a limited extent by the choice of travel-time transformation.

3.5. Comparison With Previous Literature

The direction of the primary finding is consistent with literature showing that iron-chelation adherence is associated with factors beyond conventional clinical characteristics. Household income was associated with adherence among Malaysian adolescents with transfusion-dependent thalassemia (Mohamed et al., 2022), while financial constraints were reported as barriers to continuing chelation therapy in Bangladesh (Barua et al., 2021). Travel time to the treatment center and annual transfusion burden were identified as predictors of non-adherence in Pakistani children with β-thalassemia major (Kanwal et al., 2022). A 2026 multicenter study in pediatric β-thalassemia major using the Treatment Adherence Scale additionally reported adherence associations with age, urban residence, chelation regimen, and serum ferritin (Muneeb et al., 2026). Long travel distance has also been identified as a treatment-adherence barrier in qualitative research (Emami Zeydi et al., 2017), and recent reviews emphasize a multifactorial framework in which patient, medication, access, and healthcare-system factors are associated with adherence (Wang et al., 2025).

The present study differs from these studies in its analytical question. Rather than testing the independent association of individual socioeconomic variables with adherence, it evaluated whether a prespecified socioeconomic and healthcare-access variable block provided additional discriminatory information beyond a broad demographic/clinical/treatment reference set.

The AUC increase observed in Logistic Regression was limited in absolute magnitude. Nevertheless, the already high AUC of the reference model suggests that there was limited room for additional improvement in discrimination from the added variables. Furthermore, the failure to reproduce a similar ΔAUC consistently across nonlinear models limits interpretations that the socioeconomic/access block provides model-class-independent and consistent incremental discriminatory information. One possible explanation is that the nonlinear reference models captured a larger proportion of the discriminatory patterns in the existing clinical and treatment variables, leaving less room for an additional AUC increase. This explanation is speculative and cannot be confirmed by the present analysis.

Probabilistic performance measures provide a complementary assessment. Brier-score point estimates were lower for the extended models in both the primary analysis and all three robustness models. However, the Brier score reflects overall probabilistic prediction error rather than calibration alone (Brier, 1950; Steyerberg et al., 2010). Therefore, the observed reductions in Brier score should not be interpreted on their own as evidence of improved calibration.

3.6. Strengths and Limitations

Several methodological features support the analytical consistency and reproducibility of the study. The outcome definition and cohort rules, reference and extended variable sets, primary modeling approach, preprocessing strategy, cross-validation design, classification threshold, and robustness analyses were specified before model results were examined. Reference and extended models were evaluated using identical patient-level data partitions, and all learned preprocessing steps were applied only to the corresponding training data. Hyperparameter selection was performed within inner cross-validation and separated from outer test evaluation. After results were observed, no outlier removal, class-balancing resampling, feature selection, outcome redefinition, or threshold optimization was performed.

Nevertheless, important limitations remain. First, the analysis is based on a secondary cross-sectional dataset collected at a single diagnostic center in Pabna, Bangladesh. Temporal relationships and causal effects therefore cannot be evaluated, and generalizability to other centers, populations, or healthcare systems has not been demonstrated. Because the final cohort comprised actively chelated patients with Thalassemia Major or Intermedia, the findings do not address Thalassemia Minor or patients not receiving active chelation. In the source dataset, chelation adherence was recorded using the Low, Medium, High, and N/A categories, but the source report did not provide the operational criteria, threshold values, recall interval, or a validated adherence instrument used to assign these categories (Ayon et al., 2025b). Accordingly, the endpoint should be interpreted as documented adherence and could not be independently verified in the present analysis using prospective pill counts, electronic monitoring, pharmacy-refill data, or a validated adherence scale. Heterogeneity in adherence measurement is also a recognized issue in the thalassemia literature (Locke et al., 2022; Reddy et al., 2022).

Relatedly, predictor and adherence measurements were not established as temporally ordered baseline-before-outcome observations. Contemporaneous variables such as serum ferritin, transfusion frequency, and current chelation regimen may partly reflect prior adherence, disease course, or treatment decisions. The very high AUC values should therefore be interpreted as cross-sectional discrimination of documented adherence rather than prospective prediction from clean antecedent baseline predictors. This temporal/clinical entanglement is distinct from computational leakage, which was addressed through training-only preprocessing, nested model selection, and outer-fold evaluation.

Second, the prespecified binary outcome definition combined the Medium and Low adherence categories into one class. Although this prevented post hoc redefinition of the outcome based on analysis results, it resulted in the loss of some information contained in the original adherence categories.

Third, no independent external validation cohort was available. The very high AUC values observed, particularly for the nonlinear reference models, should therefore not be interpreted as evidence that the same discrimination would be achieved in different centers, populations, or healthcare systems.

Fourth, paired bootstrap confidence intervals were calculated from the aggregated patient-level out-of-fold predictions. These intervals quantify uncertainty conditional on the saved predictions and do not incorporate all uncertainty associated with regenerating cross-validation partitions, reselecting hyperparameters, and rerunning the complete analysis process.

Finally, the incremental AUC increase observed in the primary Logistic Regression analysis was not consistently reproduced across other model classes. This is not merely a technical detail but an important result that directly limits interpretation of the finding. Accordingly, no inference can be made that the socioeconomic/access block provides consistent, model-independent incremental discriminatory information across different model classes.

CONCLUSION AND RECOMMENDATIONS

This study evaluated whether socioeconomic and healthcare-access information provides incremental discriminatory information for documented iron-chelation adherence beyond an already strong reference model comprising demographic, clinical, laboratory, transfusion, and treatment characteristics in an analytic cohort of actively chelated patients with Thalassemia Major or Intermedia.

In the prespecified Logistic Regression analysis, adding residence type, education level, monthly household income, and travel time to hospital increased ROC-AUC from 0.9514 to 0.9647, yielding ΔAUC 0.0133 (95% CI 0.0017 to 0.0259). The extended model also had a lower Brier score and produced more favorable performance measures at the fixed 0.50 threshold.

The direction of the incremental AUC finding observed in the primary analysis was preserved when raw travel time was used instead of the prespecified log1p transformation, and its magnitude changed only to a limited extent. However, similar AUC increases were not consistently reproduced across RBF-SVM, Random Forest, and XGBoost. The contribution of the socioeconomic/access block should therefore not be interpreted as a consistent improvement independent of model class. The findings indicate that the limited incremental discriminatory information observed in Logistic Regression may depend on the modeling approach used.

The results support further evaluation of socioeconomic and healthcare-access information alongside demographic, clinical, laboratory, transfusion, and treatment characteristics in studies of iron-chelation adherence. Future studies should examine the incremental value of these variables in prospective,

multicenter cohorts using standardized or objective adherence measures and independent external validation. Longitudinal designs may allow evaluation of whether socioeconomic and access-related factors provide additional information about changes in adherence over time.

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ÇELTİK YAPRAK HASTALIKLARININ CONVNEXT-TINY İLE SINIFLANDIRILMASINDA EĞİTİM VERİSİ AZLIĞI, GÖRÜNTÜ BOZULMALARI VE ÇEKİM ORTAMI FARKININ NİCEL DEĞERLENDİRMESİ

A QUANTITATIVE ASSESSMENT OF TRAINING-DATA SCARCITY, IMAGE CORRUPTIONS AND ACQUISITION-ENVIRONMENT DIFFERENCE IN RICE LEAF DISEASE CLASSIFICATION WITH CONVNEXT-TINY

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ÖZET
Bitki hastalıklarının görüntüden sınıflandırılmasında yayımlanan başarı değerleri, kontrollü koşullarda çekilmiş görüntüler ve büyük eğitim kümeleri varsayımına dayanmaktadır. Saha koşulları bu iki varsayımı birlikte ihlal eder: etiketli görüntü sayısı sınırlıdır ve görüntüler düşük çözünürlük, bulanıklık, sensör gürültüsü ve yüksek oranlı JPEG sıkıştırması içerir. Bu çalışmada, beş çeltik yaprak hastalığından oluşan Dhan-Shomadhan veri seti üzerinde tek bir mimari (ImageNet ön eğitimli ConvNeXt-Tiny) kullanılarak eğitim verisi azlığı ile dört sentetik görüntü bozulmasının tekil ve birleşik etkileri nicel olarak incelenmiştir. On saniyelik EXIF çekim grubuna duyarlı beş katlı bölme ile 20 model eğitilmiş, 1.106 görüntülük havuzlanmış kat-dışı değerlendirme kümesi üzerinde 81.844 yinelenmeyen tahmin üretilmiştir. Tam eğitim verisiyle temiz Macro-F1 %74,4 olarak ölçülmüş, eğitim verisinin %10'a indirilmesi 25,7 yüzde puanlık kayba yol açmıştır. Orta şiddetli dört bozulmanın her birinde Macro-F1, temiz koşuldaki %25 veri düzeyinin altında kalmış; orta şiddetli Gauss gürültüsünde ise %10 düzeyinin de altına inmiştir. Bu iki karşılaştırma bootstrap tekrarlarının sırasıyla en az %99,9 ve %99,0'ında doğrulanmıştır. Beyaz zeminli görüntüler ile tarla ortamındaki görüntüler arasında tam veride 12,5 yüzde puanlık gözlemsel çekim ortamı farkı bulunmuş, bu fark azaltılmış veri düzeylerinde yaklaşık 21 yüzde puana çıkmıştır. Düşük ve orta şiddetli çözünürlük kaybı tarla görüntülerinde beyaz zeminlilere göre 20,1 ve 25,2 yüzde puan daha fazla kayba yol açarken, ağır Gauss gürültüsünde tarla görüntüleri 10,8 yüzde puan daha az kaybetmiştir. Temiz koşulda sınıf bazında F1 değerleri %62,0 ile %91,8 arasında değişmiş ve beş hastalık üç istatistiksel kademeye ayrılmıştır. Beş etkenli Shapley ayrıştırması, birleşik 53,6 yüzde puanlık kaybın %29,7'sini Gauss gürültüsüne, %24,3'ünü veri azlığına atfetmiştir. Az veriyle eğitilen modelin mutlak bozulma kaybının daha küçük olması dayanıklılık olarak değil taban etkisi olarak açıklanmıştır: ağır Gauss gürültüsü altında Macro-F1, önsel eşleşmeli rastgele sınıflandırıcı referansının (%20,0) simülasyon dağılımı içine düşmektedir.
Anahtar kelimeler: Çeltik Yaprak Hastalıkları, ConvNeXt, Veri Azlığı, Dayanıklılık, Alan Kayması

ABSTRACT
Reported accuracies in image-based plant disease classification rest on two assumptions: controlled acquisition and abundant labelled data. Field conditions violate both at once, because the number of labelled images is limited and the images themselves carry low resolution, blur, sensor noise and high-ratio JPEG compression. Using the five-class Dhan-Shomadhan rice leaf dataset and a single architecture (ImageNet-pretrained ConvNeXt-Tiny), this study quantifies the individual and joint effects of training-data scarcity and four synthetic image corruptions. Twenty models were trained under a five-fold split that respects ten-second EXIF capture groups, yielding 81,844 unique predictions over a pooled out-of-fold evaluation set of 1,106 images. Clean Macro-F1 with full training data was 74.4%, and reducing training data to 10% cost 25.7 percentage points. Under each of the four medium-severity corruptions, Macro-F1 fell below the value obtained with 25% of the training data in the clean condition,

and medium Gaussian noise alone fell below the 10% level; these two comparisons held in at least 99.9% and in 99.0% of bootstrap replicates respectively. An observational acquisition-environment gap of 12.5 percentage points was found between white-background and field images at full data, widening to roughly 21 points at reduced data levels. Low and medium resolution loss cost field images 20.1 and 25.2 points more than white-background images, whereas under severe Gaussian noise field images lost 10.8 points less. Per-class F1 in the clean condition ranged from 62.0% to 91.8% and separated the five diseases into three statistical tiers. A five-factor Shapley decomposition attributed 29.7% of the 53.6-point joint loss to Gaussian noise and 24.3% to data scarcity. The smaller absolute corruption loss of low-data models is explained as a floor effect rather than robustness: under severe Gaussian noise, Macro-F1 falls within the simulated distribution of a prior-matched random classifier (20.0%).
Keywords: Rice Leaf Disease, ConvNeXt, Data Scarcity, Robustness, Domain Shift

1. GİRİŞ

Bitki hastalıklarının görüntüden otomatik tanınması, derin öğrenmenin tarımda en çok çalışılan uygulama alanlarından biridir ve literatürde sıklıkla %95'in üzerinde başarı değerleri bildirilmektedir. Bu değerlerin saha koşullarına ne ölçüde aktarılabileceği ise ayrı bir sorudur. Mohanty, Hughes ve Salathé (2016), PlantVillage veri setinde ayrılmış test kümesinde %99,35 doğruluk elde ettikten sonra aynı modeli farklı koşullarda çekilmiş görüntülerde sınadıklarında doğruluğun %31 civarına indiğini bildirmiş; sonuçlarının tekdüze arka plan üzerinde, yukarı bakan tek yaprak görüntülerine sınırlı olduğunu belirtmiştir. Bu uçurum alanın merkezî sorununu tanımlar: kontrollü çekim koşullarında ölçülen başarı, sahada karşılaşılan koşullarda korunmamaktadır.

Uçurumun iki kaynağı literatürde çoğunlukla ayrı ayrı incelenmiştir. Birincisi eğitim verisinin niceliği ve çeşitliliğidir; Barbedo (2018b) sınıf başına görüntü sayısının belirleyici etken olduğunu göstermiş, aynı yazar (Barbedo, 2018a) derin öğrenmenin bu alandaki kullanımını kısıtlayan etkenleri ayrıca ele almıştır. İkincisi görüntü kalitesi ve çekim ortamıdır; Hendrycks ve Dietterich (2019) gürültü, bulanıklık, pikselleşme ve JPEG sıkıştırmasını standart şiddet düzeyleriyle tanımlayan ImageNet-C ölçütünü önermiş ve modern sınıflandırıcıların bu bozulmalara beklenenden çok daha kırılgan olduğunu göstermiştir. Çekim ortamının kendisi de bir yanlılık kaynağıdır: Noyan (2022), PlantVillage'da yalnızca arka plandan alınmış sekiz pikselle eğitilen bir modelin %2,6'lık şans düzeyine karşı %49,0 doğruluk elde ettiğini göstermiştir.

Bu iki kaynağın birlikte nasıl davrandığı açık bir sorudur. Sahada iki dezavantaj eş zamanlı ortaya çıkar: az sayıda etiketli görüntüyle eğitilmiş bir model, karmaşık arka planlı ve düşük kaliteli bir telefon fotoğrafı üzerinde çalıştırılır. Pratik açıdan kritik soru, hangi yatırımın daha çok geri döndüğüdür: daha fazla görüntü toplamak mı, çekim kalitesini standartlaştırmak mı? Üçüncü bir sorun ölçümün kendisiyle ilgilidir. Kapoor ve Narayanan (2022), on yedi alanda 329 makaleyi etkileyen veri sızıntısı sorunlarını belgelemiş ve bu hataların makale metninden okunarak yakalanamadığını vurgulamıştır. Bitki hastalığı veri setleri bu riske özellikle açıktır: saha çalışmasında aynı yaprak genellikle üst üste birkaç kez fotoğraflanır.

Bu çalışmanın katkıları üç başlıkta toplanmaktadır. Birincisi, çekim grubuna duyarlı bir değerlendirme protokolü kurulmuş ve zamansal bağımlılığın üç ayrı kanalı ayrı ayrı denetlenmiştir. İkincisi, veri azlığı ayrı bir çalışma olarak değil dört bozulmayla çaprazlanan ana eğitim faktörü olarak ele alınmış; birleşik kayıp, toplamı gözlenen kayba tam olarak eşitlenen Shapley ayrıştırmasıyla faktörlere paylaştırılmıştır. Üçüncüsü, her bozulmanın maliyeti atılmış eğitim verisi birimiyle ifade edilmiş; böylece dayanıklılık ölçümü, veri toplama ile çekim kalitesi arasındaki takası niceleyen bir karar çıktısına dönüştürülmüştür. Çalışma bilinçli olarak tek bir mimariyle sınırlandırılmıştır; amaç en iyi modeli bulmak değil, sabit bir mimari altında saha dezavantajlarının etkisini ölçmektir.

2. MATERYAL VE YÖNTEM

2.1. Veri seti

Çalışmada, Bangladeş yerel çeltik çeşitlerinden derlenmiş Dhan-Shomadhan veri seti kullanılmıştır (Hossain, Abujar, Noori & Hossain, 2021). Veri seti 1.106 görüntü ve beş hastalık sınıfı içermektedir: Brown Spot, Leaf Scald, Rice Blast, Rice Tungro ve Sheath Blight. Görüntüler doğal tarla arka planı (337 görüntü) ve tekdüze beyaz zemin (769 görüntü) olmak üzere iki çekim ortamında toplanmıştır (Tablo 1). Veri setinde sağlıklı sınıf bulunmadığından çalışmanın görevi hastalık var/yok tespiti değil, beş hastalık arasında ayırıcı sınıflandırmadır.

Tablo 1. Sınıf ve çekim ortamı bazında görüntü sayıları.

Sınıf	Tarla	Beyaz zemin	Toplam
Brown Spot	49	90	139
Leaf Scald	74	143	217
Rice Blast	74	198	272
Rice Tungro	76	119	195
Sheath Blight	64	219	283
Toplam	337	769	1.106

2.2. Veri denetimi ve karışıklık yapısı

Okunamayan veya bozuk görüntü ile tam dosya kopyası bulunmamıştır. EXIF üstverisi, bütün görüntülerin aynı cihazla 4–24 Ekim 2020 arasında yedi ayrı günde çekildiğini göstermektedir. Bu yedi günün yalnızca birinde (17 Ekim) her iki çekim ortamı birlikte kullanılmıştır. Tarla görüntülerinin %85,2'si (287/337) beyaz zemin çekimi yapılmayan günlerde, beyaz zeminli görüntülerin %71,7'si (551/769) tarla çekimi yapılmayan günlerde alınmıştır. Dolayısıyla çekim ortamı; tarih, günün aydınlatma koşulları ve çekim oturumu ile büyük ölçüde iç içe geçmiştir ve iki ortam arasındaki başarı farkı bu çalışmada nedensel bir arka plan etkisi olarak değil gözlemsel çekim ortamı farkı olarak ele alınmıştır. Sınıf ile çekim tarihi arasında da anlamlı bir ilişki bulunmuştur ($\chi^2 = 396,9$; sd = 24; $p < 0,001$; Cramér's V = 0,300); görüntülerinin %51,2'sini tek bir günden alan Sheath Blight en yoğun örnektir.

2.3. Çekim grubu tanımı ve bölme protokolü

Aynı çekim oturumundan gelen neredeyse özdeş kareler EXIF çekim zamanlarıyla gruplanmıştır: aynı hastalık ve aynı çekim ortamı içinde en fazla 10 saniye ara ile çekilmiş görüntüler tek bir çekim grubu kabul edilmiş ve bu gruplar bölme sırasında bölünmemiştir. Kenarların yalnızca sınıf ve ortam içinde tanımlanması, algısal hash tabanlı otomatik gruplamanın farklı hastalıkları yanlış eşleştirme sorununu ortadan kaldırmıştır. Böylece 1.106 görüntü 946 çekim grubuna ayrılmış, en büyük grup 6 görüntü içermiştir. Bu pencerenin seçimine bağlı duyarlılık Bölüm 3.9'da ele alınmıştır.

Bölme, sınıf × çekim ortamı üzerinde tabakalı ve çekim grubu düzeyinde beş katlı çapraz doğrulama ile kurulmuştur. Her görüntü tam olarak bir dış katta test edilmiş, beş katın tahminleri birleştirilerek 1.106 görüntülük havuzlanmış kat-dışı değerlendirme kümesi oluşturulmuştur; bu tasarım tarla alt kümesinin kat başına yaklaşık 67 görüntüye düşmesi sorununu ortadan kaldırmaktadır. Dış katlar bağımsız deney tekrarı olarak değerlendirilmemiştir. Eğitim verisi seviyeleri her kat içinde, çekim grubu düzeyinde ve iç içe üretilmiştir: %10'daki bütün gruplar %25'in, %25'teki bütün gruplar %50'nin içindedir. Kat başına yaklaşık dağılım 707–708 eğitim, 177 doğrulama ve 221–222 test görüntüsüdür.

2.4. Model ve eğitim yapılandırması

Model olarak ImageNet-1k ön eğitimli ConvNeXt-Tiny kullanılmıştır (Liu vd., 2022). Bütün katmanlar güncellenmiş, girdi boyutu 224 × 224 piksel olarak sabitlenmiş ve en-boy oranı korunarak letterbox uygulanmıştır. Eğitim artırımı yatay çevirme ($p = 0,5$) ve ±8 derece döndürme ile sınırlı tutulmuş; test edilen bozulmalar eğitim artırımı olarak kullanılmamıştır. Optimizasyon, ayrıştırılmış ağırlık çürümesi kullanan AdamW ile yapılmıştır (Loshchilov & Hutter, 2019) (öğrenme oranı 1×10^{-4}, ağırlık çürümesi 1×10^{-4}). Öğrenme oranı, kosinüs tavlama ile ve yeniden başlatma uygulanmaksızın 1×10^{-6}'ya indirilmiştir; kosinüs tavlama SGDR yönteminin bir bileşeni olarak önerilmiştir (Loshchilov & Hutter, 2017), bu çalışmada yalnızca tavlama kısmı kullanılmıştır. Kayıp fonksiyonu sınıf ağırlıklı çapraz entropi olup 0,05 etiket yumuşatması uygulanmıştır. Eğitim en fazla 25 epoch sürmüş; ilk 5 epochtan sonra doğrulama Macro-F1 değerine göre 5 epoch sabırlı erken durdurma kullanılmıştır. Dört veri düzeyi ve beş kat için toplam 20 model eğitilmiştir.

2.5. Test zamanı bozulmaları

Dört bozulma, ImageNet-C'nin standart şiddet düzeyleri esas alınarak uygulanmıştır (Hendrycks & Dietterich, 2019): Gauss gürültüsü, Gauss bulanıklığı, pikselleşme ve JPEG yeniden sıkıştırması. Her bozulma üç şiddette (seviye 1, 3 ve 5) kullanılmıştır. Şiddetler model performansına bakılarak

seçilmemiştir; en zararlı faktörü araştıran bir çalışmada şiddeti etkisine göre ayarlamak döngüsel olacağından yerleşik ölçütün tanımlı değerleri kullanılmıştır (Tablo 2). Bozulmalar şu sabit sırada uygulanmıştır: EXIF yön düzeltmesi, 224 × 224 letterbox, bozulma, normalizasyon. Gauss gürültüsünün gerçekleşmesi görüntü kimliği, bozulma türü ve şiddetten türetilen bir tohumla üretilmiş; böylece bütün modeller aynı görüntü için aynı gürültü örneğini görmüştür ve koşullar arası karşılaştırmalar eşleştirilmiştir. Şekil 1, orta şiddetli bozulmaların iki çekim ortamındaki görünümünü vermektedir.

Tablo 2. Bozulma parametreleri (ImageNet-C seviye 1, 3, 5).

Bozulma	Şiddet 1	Şiddet 3	Şiddet 5
Gauss gürültüsü, σ ([0,1] ölçeğinde)	0,08	0,18	0,38
Gauss bulanıklığı, σ (piksel)	1	3	6
Pikselleşme ölçeği	0,60	0,40	0,25
JPEG kalitesi	25	15	7



Şekil 1. Orta şiddetli (seviye 3) bozulmaların 224 × 224 letterbox sonrası görünümü. Satırlar solda etiketlenmiştir; sütun başlıkları yalnızca üstte verilmiştir. Yan bantlar letterbox dolgusudur; uzun ve ince yaprak kareye sığdırıldığı için girdinin önemli bir bölümü dolgudan oluşmaktadır.

2.6. Ölçütler ve istatistiksel çıkarım

Birincil ölçüt havuzlanmış kat-dışı Macro-F1, ikincil ölçüt doğruluktur. Etki büyüklükleri birincil olarak yüzde puan, ikincil olarak göreli yüzde kayıp cinsinden verilmiştir. Belirsizlik, sınıf × çekim ortamı tabakalı ve çekim grubu duyarlı bootstrap ile 2.000 tekrar üzerinden hesaplanmıştır; bir koşulun bütün tekrarları tek bir ağırlık matrisiyle üretildiği için koşullar arası bütün farklar eşleştirilmiştir. Sıralama iddiaları, güven aralıklarının örtüşmesine değil farkın kendi aralığına dayandırılmış; ayrıca çekim grubu düzeyinde eşleştirilmiş işaret-değiştirme permütasyon testi uygulanmış ve aile içinde Benjamini–Hochberg düzeltmesi yapılmıştır (Benjamini & Hochberg, 1995). Bir sıralama iddiası yalnızca güven aralığı sıfırı dışladığında ve düzeltilmiş p değeri 0,05'in altında kaldığında kurulmuştur. Permütasyon testi, koşul etiketinin çekim grubu içinde takas edilebildiği karşılaştırmalarda kullanılmıştır: bozulmaların birbirine göre sıralaması ve komşu şiddetler. Buna karşılık iki aile bootstrap güven aralığının tersine çevrilmesine dayanmaktadır. Birincisi, farklı veri düzeylerinde eğitilmiş iki modelin karşılaştırıldığı çekim ortamı açığı farklarıdır; burada değiştirilebilirlik varsayımı geçerli değildir. İkincisi çekim ortamı × bozulma ailesidir: bu ailede sınanan sıfır hipotezi bozulma kaybının iki ortamda eşit olmasıdır (fark-farkı = 0), oysa çekim grubu içinde temiz–bozuk etiketini takas eden işaret-değiştirme şeması "bozulmanın hiçbir etkisi olmaması" hipotezini kurar ve büyük ana etkiyi sıfır dağılımının yayılımına kattığı için etkileşim sınamasında muhafazakâr davranır. Ortam etiketini gruplar arasında permüte etmek etkileşim hipotezini doğrudan hedeflerdi; ancak çekim ortamı hem çekim günüyle (yedi günün yalnızca birinde iki arka plan birlikte bulunmaktadır) hem sınıfla (Cramér's V =

0,300) karışık olduğundan bu şema burada uygulanabilir değildir. Ayrım sonuç dosyalarında da işaretlenmiştir. Tablo 3, 4 ve 5'teki birincil kontrastlar önceden belirlenmiş olup çoklu karşılaştırma düzeltmesi taşımaz.

Referans başarı düzeyi olarak önsel eşleşmeli rastgele sınıflandırıcı kullanılmıştır. Tahminlerin sınıf önselinden bağımsız çekildiği böyle bir sınıflandırıcıda sınıf i için duyarlılık ve kesinlik p_i'ye eşit olduğundan $F1_i = p_i$ ve Macro-F1 = ortalama(p_i) = 1/K'dır; bu referans dolayısıyla sınıf dengesizliğinden bağımsız olarak %20,0'dir ve simülasyon %19,97 vermiştir. Bu tek bir evrensel şans sınırı değil, seçilen bir referanstır: düzgün rastgele sınıflandırıcı %19,7, çoğunluk sınıfı ise %8,2 vermektedir.

Birleşik kaybın paylaştırılmasında, dört bozulmanın orta şiddeti ile veri azlığı (%100'den %10'a) beş oyunculu bir işbirlikçi oyun olarak modellenmiş ve $2^5 = 32$ koşul üzerinden tam Shapley değerleri hesaplanmıştır (Shapley, 1953). Değer fonksiyonu tam veri ve temiz koşula göre yüzde puan kaybı olarak tanımlanmış olup etkinlik aksiyomu gereği Shapley değerlerinin toplamı gözlenen birleşik kayba eşitlenir. Birleşik koşullarda bozulmalar sabit sırada uygulanmıştır; sonuçlar bu tanımlı zincire aittir. Değerlendirme, 20 model üzerinde 13 ana koşul (57.512 kayıt) ve 32 Shapley koşulu (35.392 kayıt) olmak üzere 92.904 kayıt üretmiştir; 11.060 örtüşen kayıt çıkarıldığında 81.844 yinelenmeyen tahmin kalmaktadır. Sınıf bazında F1 güven aralıkları, kuşatma kararlarının bootstrap kararlılığı ve pikselleşme kontrastları aynı küme-duyarlı bootstrap üzerinden hesaplanmıştır. Bütün değerler, katlar arası yayılımın örnekleme belirsizliğinden büyük olması nedeniyle tek ondalığa yuvarlanmıştır.

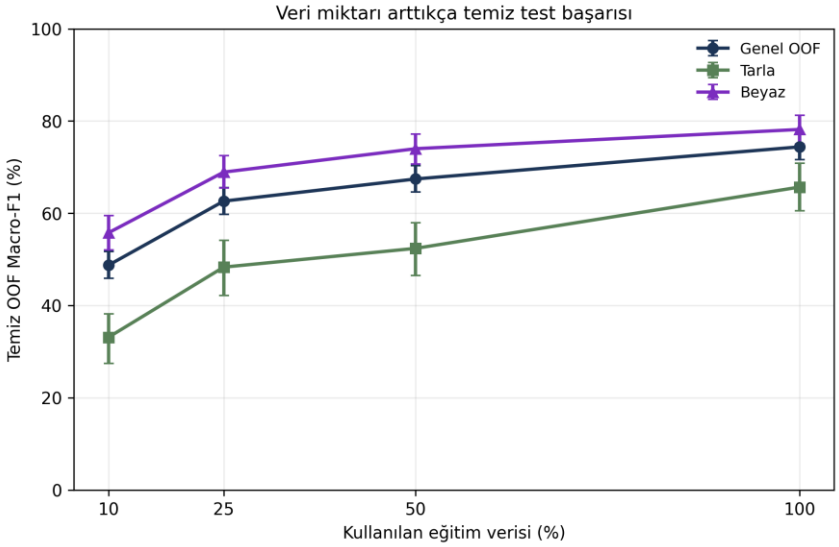
3. BULGULAR VE TARTIŞMA

3.1. Eğitim verisi azlığının etkisi

Eğitim verisinin %100'den %10'a indirilmesi temiz Macro-F1'i 25,7 yüzde puan düşürmüştür; bu, tam veri başarısına göre %34,5 göreli kayıptır (Tablo 3). En büyük tek adımlı kazanç %10'dan %25'e geçişte görülmüş, Macro-F1 13,9 yüzde puan yükselmiştir; %50'den %100'e geçişteki kazanç 7,0 yüzde puandır. Öğrenme eğrisi en düşük düzeyde bile referans düzeyin belirgin biçimde üzerinde kalmakta, ancak doyuma ulaşmamaktadır (Şekil 2).

Tablo 3. Temiz koşulda veri azlığının etkisi (havuzlanmış kat-dışı değerlendirme, %95 güven aralığı).

Eğitim verisi	Macro-F1	%95 GA	Tam veriye göre kayıp	Göreli kayıp
%10	%48,7	45,9–51,7	25,7 yp (22,3–29,1)	%34,5
%25	%62,6	59,8–65,5	11,8 yp (8,8–14,6)	%15,8
%50	%67,4	64,6–70,3	7,0 yp (4,5–9,4)	%9,4
%100	%74,4	71,7–77,2	—	—



Şekil 2. Temiz koşulda eğitim verisi miktarına göre havuzlanmış kat-dışı Macro-F1. Hata çubukları küme duyarlı bootstrap %95 güven aralığıdır.

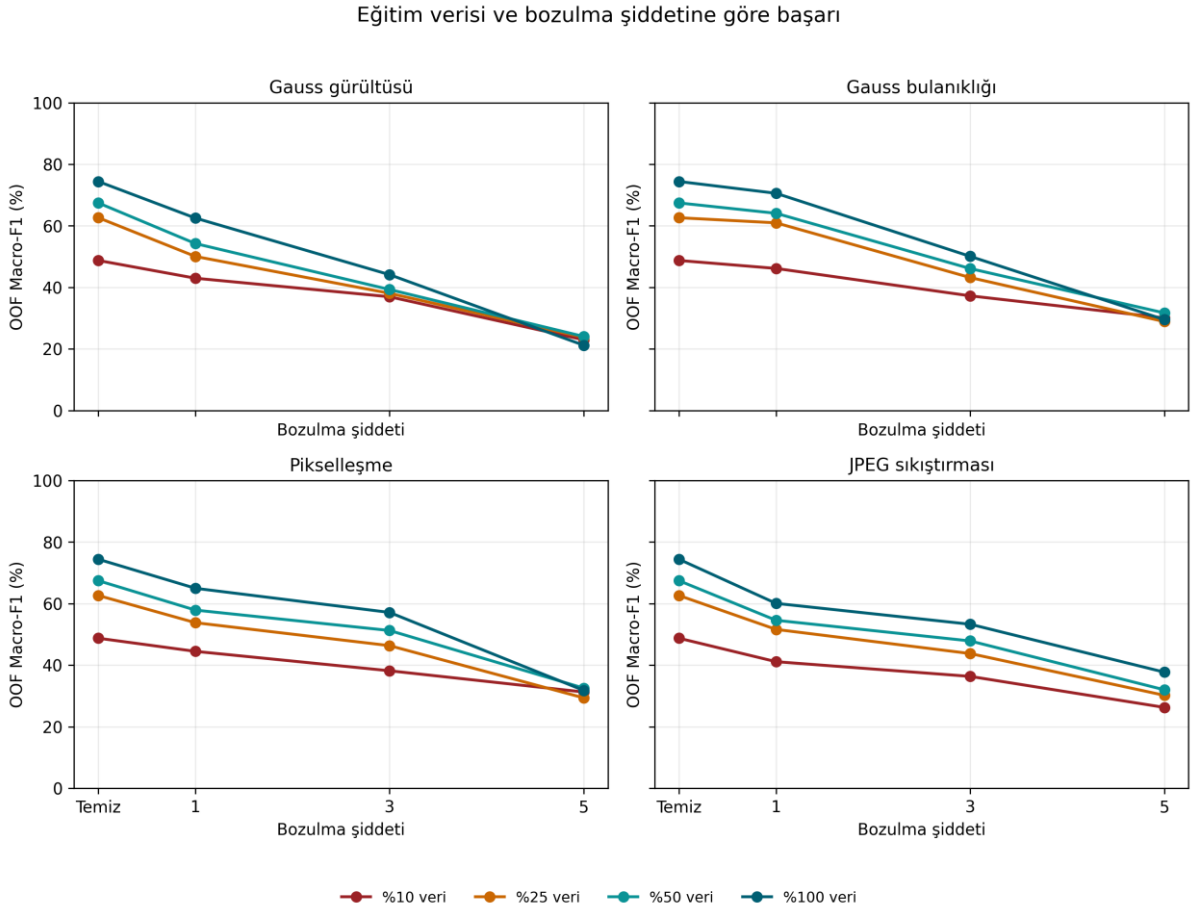
3.2. Görüntü bozulmalarının etkisi

Bütün faktörlerde komşu şiddetler arasındaki artış anlamlıdır (sekiz karşılaştırmanın sekizinde düzeltilmiş $p < 0{,}001$), incelenen 1, 3 ve 5 şiddetlerinde kayıp monoton biçimde artmıştır (Tablo 4, Şekil 3). Düşük şiddette en büyük kayıplar JPEG sıkıştırması (14,3 yp) ve Gauss gürültüsündedir (11,9 yp); bu iki bozulma arasındaki fark istatistiksel olarak ayırt edilememiştir (−2,5 yp; %95 GA −5,5 ile +0,4; düzeltilmiş $p = 0{,}136$). Aynı şiddette en küçük kayıp Gauss bulanıklığındadır (3,8 yp) ve bu fark diğer üç bozulmanın hepsine karşı anlamlıdır. Orta ve yüksek şiddette ise Gauss gürültüsünün kaybı diğer üçünden anlamlı biçimde büyüktür (orta şiddette bulanıklığa karşı 6,0 yp, JPEG'e karşı 9,2 yp, pikselleşmeye karşı 13,0 yp; hepsinde düzeltilmiş $p \leq 0{,}003$).

Bu desen, düşük şiddette agresif sıkıştırmanın, yüksek şiddette ise sensör gürültüsünün baskın risk olduğunu göstermektedir. Ağır Gauss gürültüsü altında Macro-F1 %74,4'ten %21,2'ye inmiştir; bu değer, önsel eşleşmeli rastgele sınıflandırıcının simülasyon dağılımındaki merkezî %95 aralığın (%17,8–%22,2) içinde kalmaktadır. Şekil 3'te dört veri düzeyinin eğrilerinin şiddet 5'te birleşmesi, Bölüm 3.7'de ele alınan taban etkisinin görsel karşılığıdır.

Tablo 4. Tam veriyle eğitilmiş modelde bozulma kayıpları (yüzde puan, %95 güven aralığı).

Bozulma	Şiddet 1	Şiddet 3	Şiddet 5
Gauss gürültüsü	11,9 (9,3–14,5)	30,3 (26,8–33,8)	53,2 (49,9–56,7)
Gauss bulanıklığı	3,8 (1,8–5,9)	24,3 (20,9–27,7)	44,9 (41,4–48,5)
Pikselleşme	9,4 (6,9–12,1)	17,3 (14,4–20,2)	42,6 (39,3–46,0)
JPEG sıkıştırması	14,3 (11,6–17,2)	21,1 (18,2–24,2)	36,7 (33,2–40,3)



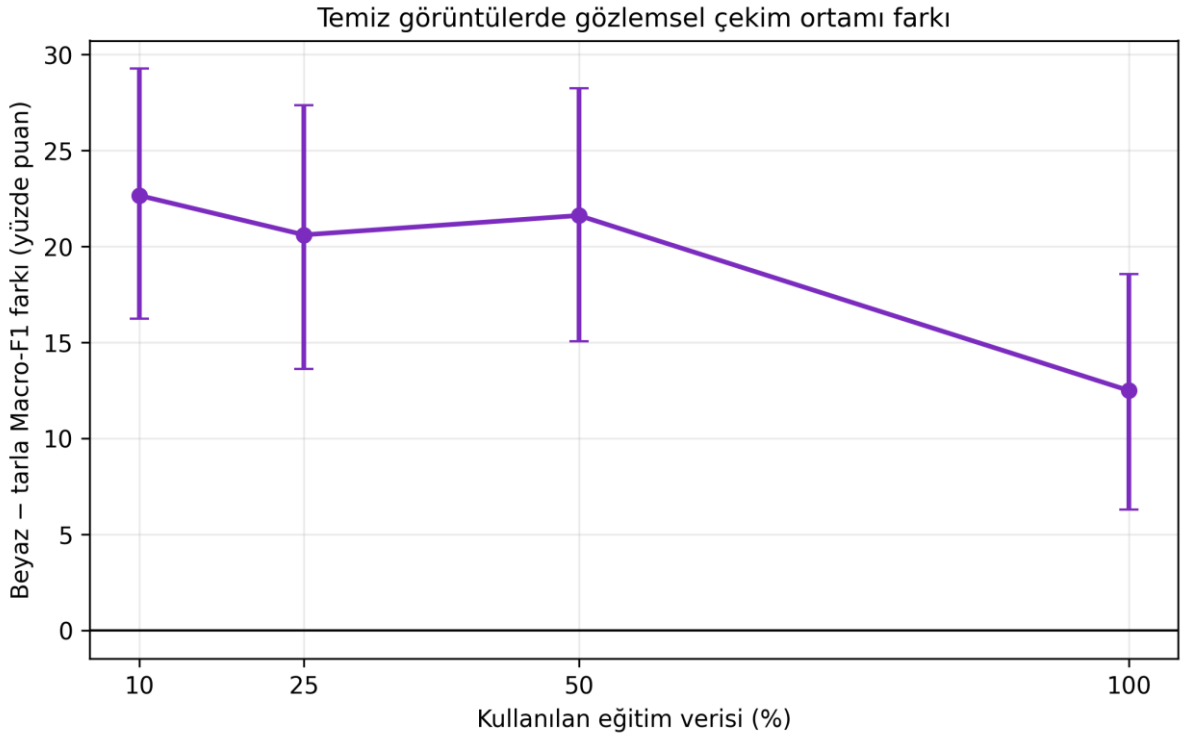
Şekil 3. Eğitim verisi miktarı ve bozulma şiddetine göre Macro-F1. Şiddet 5'te dört veri düzeyinin eğrileri birleşmekte; JPEG panelinde ise ayrı kalmaktadır.

3.3. Çekim ortamı farkı

Gözlemsel çekim ortamı farkı, azaltılmış bütün eğitim düzeylerinde yaklaşık 21 yüzde puandır (%10'da 22,7; %25'te 20,6; %50'de 21,6) ve yalnızca tam eğitim verisinde 12,5 yüzde puana düşmektedir (Tablo 5, Şekil 4). Açıkların farkı doğrudan test edildiğinde bu düşüş ayırt edilebilir bulunmuştur (%10'a göre fark 10,2 yp; %95 GA 2,5–18,3; düzeltilmiş p = 0,013; %25 ve %50 için de anlamlı). Desen kademeli bir daralma değil, tam veride görülen bir basamaktır. Bulgu, tam veriyle eğitilen modelin iki çekim ortamı arasındaki farkı kısmen telafi ettiğine işaret eder; ancak açık tam veride de ortadan kalkmamaktadır ve Bölüm 2.2'deki tarih karışıklığı nedeniyle nedensel bir arka plan etkisi olarak yorumlanmamalıdır.

Tablo 5. Temiz koşulda çekim ortamına göre Macro-F1 ve gözlemsel fark.

Eğitim verisi	Tarla	Beyaz zemin	Beyaz − tarla	%95 GA
%10	%33,1	%55,8	22,7 yp	16,2–29,3
%25	%48,3	%68,9	20,6 yp	13,6–27,4
%50	%52,4	%74,0	21,6 yp	15,1–28,2
%100	%65,7	%78,2	12,5 yp	6,3–18,6

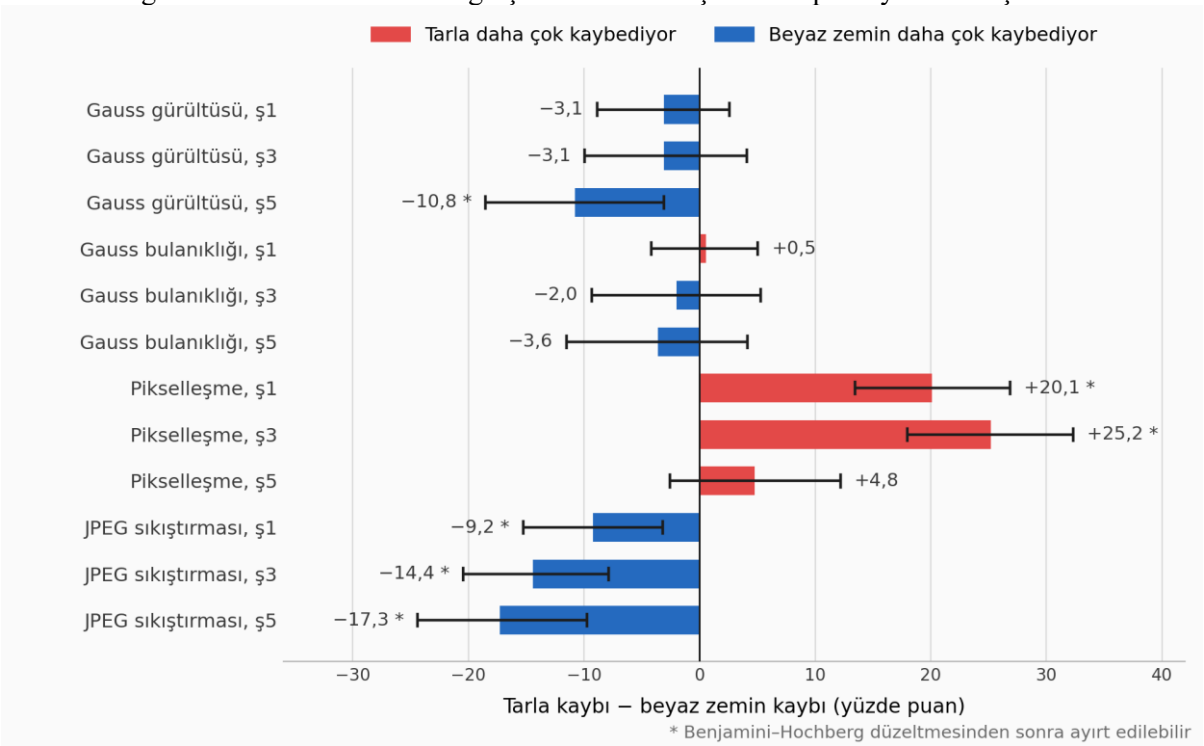


Şekil 4. Temiz koşulda tarla ve beyaz zemin alt kümelerinde Macro-F1 ile aralarındaki gözlemsel fark.

3.4. Çekim ortamı ile bozulmaların etkileşimi

Bozulma kayıpları iki çekim ortamında ayrı hesaplandığında iki farklı davranış ortaya çıkmaktadır (Şekil 5). Gürültü, bulanıklık ve JPEG için tarla görüntülerindeki mutlak kayıp beyaz zeminlilerden küçüktür; bu, tarla alt kümesinin temiz başarısının zaten düşük olmasından kaynaklanan bir taban etkisiyle uyumludur. Pikselleşme ise ters yönde davranmaktadır: tam eğitim verisinde düşük ve orta şiddetli çözünürlük kaybı, tarla görüntülerinde beyaz zeminlilere göre sırasıyla 20,1 ve 25,2 yüzde puan daha fazla kayba yol açmıştır (%95 GA 13,4–26,9 ve 18,0–32,3; her ikisinde düzeltilmiş p = 0,0015). Pikselleşmenin bu davranışı doğrudan test edilmiştir: çekim ortamı etkileşimi, diğer üç bozulmanın ortalamasından her üç şiddette de anlamlı biçimde farklıdır (şiddet 1: +24,0 yüzde puan, %95 GA 17,7–30,5; şiddet 3: +31,7 yüzde puan, 24,9–38,4; şiddet 5: +15,3 yüzde puan, 9,7–20,5; hepsinde düzeltilmiş p < 0,001) ve dokuz ikili kontrastın dokuzu da ayırt edilebilir bulunmuştur. Şiddet 5'te pikselleşmenin kendi etkileşimi sıfırdan ayırt edilememekle birlikte (+4,8 yüzde puan), diğer üç bozulmanın belirgin

biçimde negatif etkileşimlerinden hâlâ anlamlı biçimde farklıdır. Bu kontrastlar eşleştirilmiş küme bootstrap'ının iki yanlı kuyruk olasılığına dayanmakta olup Benjamini–Hochberg düzeltmelidir. Olası mekanizma, tarla görüntülerinde yaprağın kare içinde kapladığı alanın daha küçük olması ve çözünürlük düşüşünün lezyon dokusunu daha hızlı yok etmesidir; yaprak alan oranı ölçülmediğinden bu mekanizma sınanmamıştır. Aile 48 karşılaştırmadan oluştuğu için keşifsel kabul edilmiş; bütün karşılaştırmalarda eşleştirilmiş küme bootstrap'ının iki yanlı kuyruk olasılığı ve Benjamini–Hochberg düzeltmesi kullanılmıştır. Kırk sekiz karşılaştırmanın 28'i ayırt edilebilir, biri sınırda, 19'u ayırt edilemez bulunmuştur. Ağır Gauss gürültüsünde tarla ile beyaz zemin arasındaki kayıp farkı −10,8 yüzde puandır (%95 GA −18,5 ile −3,1; düzeltilmiş p = 0,016): tarla görüntüleri, temiz başarısı zaten düşük olduğu için ağır gürültüden beyaz zeminlilere göre daha az mutlak kayıp yaşamaktadır. Aynı karşılaştırma, çekim grubu içinde temiz–bozuk etiketini takas eden daha kısıtlayıcı işaret-değiştirme şeması altında sınırda kalmaktadır (düzeltilmiş p = 0,094); Bölüm 2.6'da açıklandığı gibi bu şema etkileşim hipotezini hedeflemediği ve muhafazakâr davrandığı için birincil sonuç bootstrap'a dayandırılmıştır.



Şekil 5. Tam eğitim verisinde tarla ve beyaz zemin kayıpları arasındaki fark. Pozitif değerler tarla görüntülerinin daha çok kaybettiği koşulları gösterir. Hata çubukları küme duyarlı bootstrap %95 güven aralığıdır; yıldız, Benjamini–Hochberg düzeltmesinden sonra ayırt edilebilen karşılaştırmaları işaretler.

3.5. Sınıf bazında sonuçlar

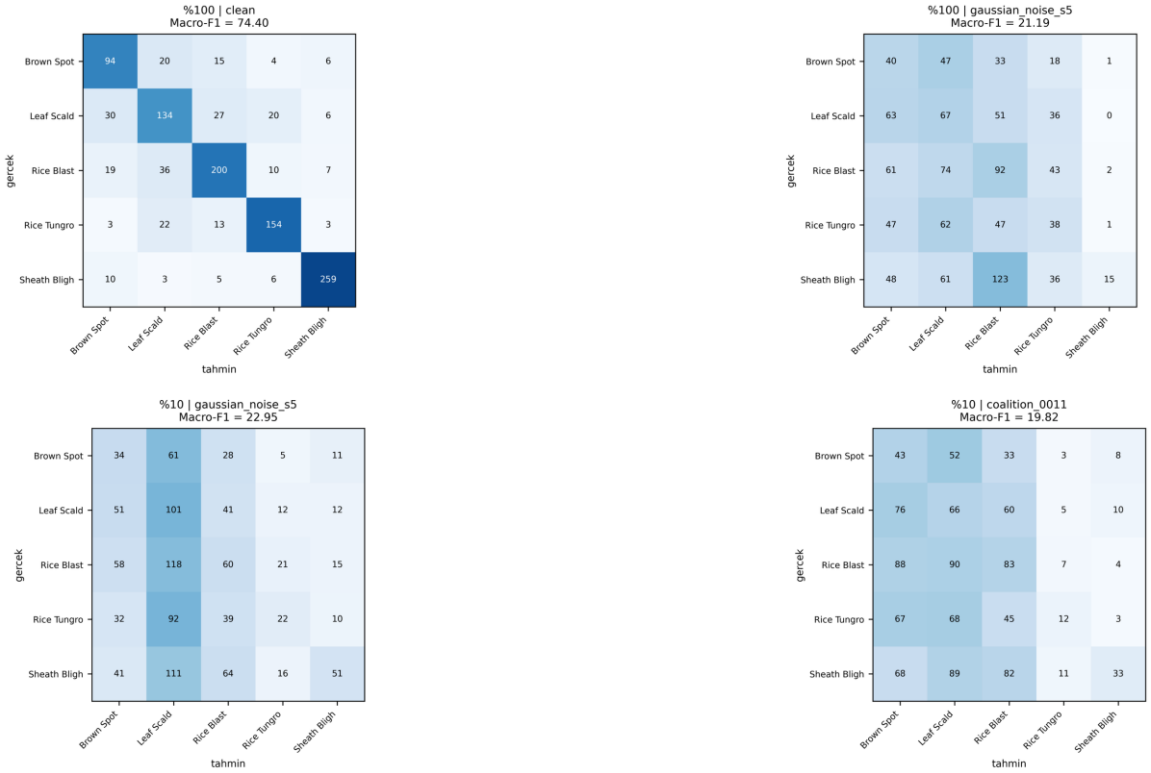
Temiz koşulda ve tam veride sınıf bazında F1 değerleri %62,0 ile %91,8 arasında değişmektedir (Tablo 6). On sınıf çiftinden sekizi Benjamini–Hochberg düzeltmesinden sonra ayırt edilebilir bulunmuş ve sınıflar istatistiksel olarak üç kademeye ayrılmıştır: Sheath Blight (%91,8) diğer dört sınıfın hepsinden anlamlı biçimde yüksektir; Rice Tungro (%79,2) ile Rice Blast (%75,2) birbirinden ayırt edilememekte, ancak alt kademeden anlamlı biçimde yüksektir; Brown Spot (%63,7) ile Leaf Scald (%62,0) da birbirinden ayırt edilememektedir. Bu kademelenme yalnızca örnek sayısıyla açıklanmamaktadır: Leaf Scald 217 görüntüye sahip olmasına karşın 195 görüntülü Rice Tungro'dan anlamlı biçimde düşük F1 vermektedir (fark 17,1 yüzde puan; %95 GA 11,3–23,1). Dolayısıyla sınıf başına görüntü sayısı başarıyı etkilemekle birlikte tek belirleyici değildir; hastalıkların görsel ayırt edilebilirliği de rol oynamaktadır. Veri azaltıldığında düşüş özellikle Brown Spot ve Leaf Scald sınıflarında daha belirgindir: %10 veride Brown Spot'un F1 değeri %32,8'e inerken Sheath Blight %72,9'da kalmaktadır. Karışıklık matrisleri (Şekil 6), ağır bozulma altında tahminlerin belirli sınıflara yığıldığını ve köşegen yapısının kaybolduğunu göstermektedir. Bu sonuçların yorumunda Bölüm 2.2'deki sınıf–tarih ilişkisi dikkate alınmalıdır; görüntülerinin %51,2'sini tek bir çekim gününden alan Sheath Blight'ta tek oturumdan gelen görüntülerin birbirine daha benzer olması ayırt edilmeyi kolaylaştırabileceğinden, sınıf bazındaki farklar

yalnızca hastalıkların görsel ayırt edilebilirliğine değil kısmen çekim oturumu bileşimine de atfedilmelidir.

Tablo 6. Temiz koşulda sınıf bazında F1 ve %95 güven aralıkları.

Sınıf	Destek	Tam veri F1 (%95 GA)	%10 veri F1 (%95 GA)	Kademe
Sheath Blight	283	91,8 (89,5–94,1)	72,9 (69,3–76,5)	1
Rice Tungro	195	79,2 (74,1–83,8)	51,9 (45,5–58,3)	2
Rice Blast	272	75,2 (71,0–79,2)	51,3 (45,6–56,5)	2
Brown Spot	139	63,7 (57,8–69,9)	32,8 (26,2–39,7)	3
Leaf Scald	217	62,0 (56,7–67,0)	34,7 (29,0–40,6)	3

Kademeler, on sınıf çifti üzerinde Benjamini–Hochberg düzeltmeli eşleştirilmiş karşılaştırmalardan türetilmiştir; aynı kademedeki sınıflar birbirinden ayırt edilememektedir.



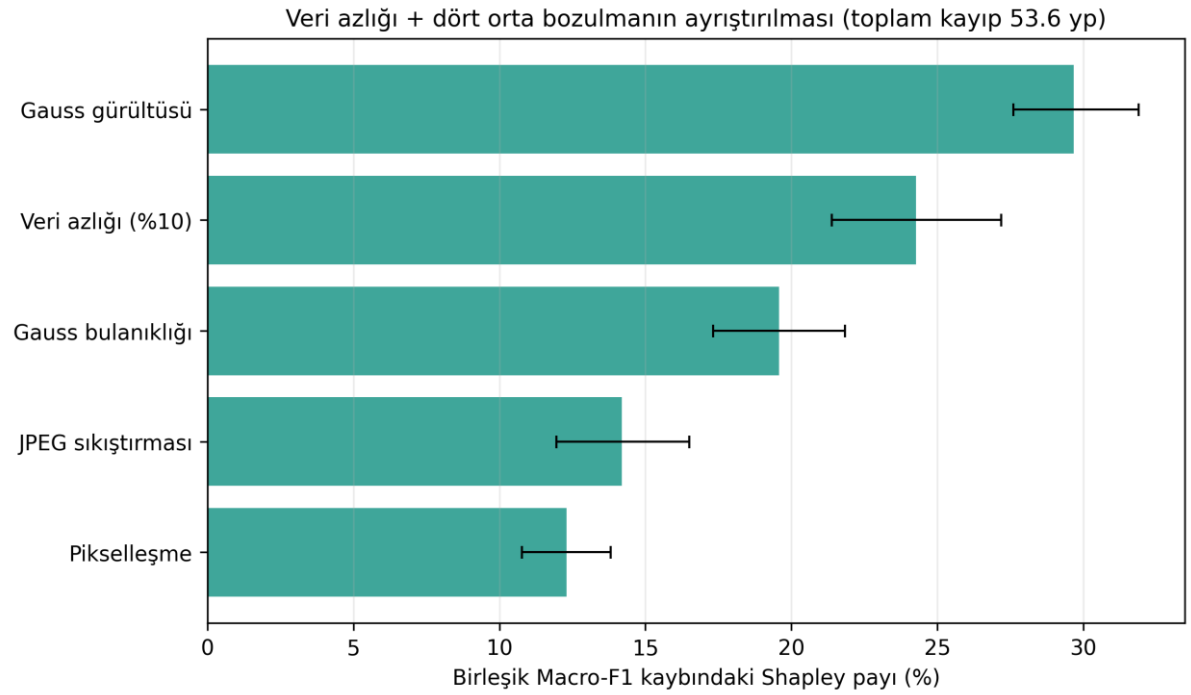
Şekil 6. Seçili koşullar için karışıklık matrisleri (havuzlanmış kat-dışı değerlendirme). Üst sol: tam veri, temiz. Üst sağ: tam veri, ağır Gauss gürültüsü. Alt sol: %10 veri, ağır Gauss gürültüsü. Alt sağ: %10 veri, dört orta şiddetli bozulma. Referans başarı düzeyi %20,0'dir; ağır gürültü koşullarında tahminler belirli sınıflara yığılmakta ve köşegen yapısı kaybolmaktadır.

3.6. Birleşik kaybın Shapley ayrıştırması

Beş etkenli oyunun başlangıç koşulu tam veri ve temiz görüntüdür (Macro-F1 = %74,4); son koşul %10 veri ve dört orta şiddetli bozulmadır (Macro-F1 = %20,8). Birleşik kayıp 53,6 yüzde puandır. En büyük pay Gauss gürültüsüne (%29,7), ikinci pay veri azlığına (%24,3) aittir (Tablo 7, Şekil 7). Macro-F1 ve doğrulukta aynı sıralama elde edilmiştir (doğrulukta gürültü %28,7; veri azlığı %25,2). Shapley değerleri faktörlerin tek başına oluşturduğu kayıplar değil, bütün faktör koalisyonlarındaki marjinal katkıların ortalamasıdır ve etkileşimleri faktörlere paylaştırır; sonuçlar tanımlı bozulma zincirine aittir.

Tablo 7. Beş etkenli Shapley ayrıştırması (Macro-F1, birleşik kayıp 53,6 yüzde puan). Satır paylarının yuvarlanmış toplamı %100,1; hesaplanan toplam %100'dür.

Etken	Shapley katkısı	%95 GA	Birleşik kayıptaki pay
Gauss gürültüsü	15,9 yp	14,5–17,4	%29,7
Veri azlığı (%100 → %10)	13,0 yp	11,1–14,8	%24,3
Gauss bulanıklığı	10,5 yp	9,1–11,9	%19,6
JPEG sıkıştırması	7,6 yp	6,3–9,0	%14,2
Pikselleşme	6,6 yp	5,6–7,5	%12,3
Toplam	53,6 yp	—	%100



Şekil 7. Birleşik Macro-F1 kaybının beş etkene Shapley paylaştırması. Paylar toplamı, etkinlik aksiyomu gereği gözlenen 53,6 yüzde puanlık kayba eşittir.

3.7. Veri azlığı bozulma hassasiyetini artırıyor mu?

Mutlak yüzde puan ölçeğinde, %10 veriyle eğitilen modelin bozulma kaybı %100 veriyle eğitilen modelden anlamlı biçimde küçüktür: on iki koşuldan on birinde farkların farkının güven aralığı sıfırı dışlamaktadır ve en büyük fark ağır Gauss gürültüsünde −27,4 yüzde puandır (%95 GA −32,0 ile −23,1). Bu bulgu, düşük veriyle eğitilen modelin daha dayanıklı olduğu biçiminde yorumlanamaz. Ağır bozulmalar altında başarı, önsel eşleşmeli rastgele sınıflandırıcının simülasyon dağılımı içine düşmektedir; referans düzey üzerinde korunan performans payı hesaplandığında tam veri modelinin ağır Gauss gürültüsü altında bu payın yalnızca %2,2'sini koruduğu görülmektedir. Kaybedilebilecek performans kalmadığı için mutlak farkların daralması bir taban etkisidir.

Ölçek etkisinden arındırmak üzere her koşulun beceri skoru aynı veri düzeyindeki temiz koşula oranlandığında iki eğitim düzeyi arasında tutarlı bir yön bulunmamaktadır: ortalama fark 3,7 puan olup on iki koşuldan yedisinde düşük veri lehine, beşinde aleyhinedir. Dolayısıyla bu çalışmanın verisi, eğitim verisi azlığının görüntü bozulmalarına karşı ek bir hassasiyet yarattığı hipotezini ne desteklemekte ne de çürütmektedir. Ölçülen şey, veri azlığının hem temiz hem bozulmuş koşullarda mutlak başarıyı bağımsız ve büyük ölçüde düşürdüğüdür.

3.8. Bozulma maliyetinin eğitim verisi cinsinden ifadesi

Temiz öğrenme eğrisi dört ölçülmüş noktadan oluştuğu için, her bozulmuş koşulun bu eğride hangi iki veri düzeyi arasına düştüğü enterpolasyon yapılmaksızın belirlenebilir (Tablo 8). Sonuçlar iki ifadeye izin vermektedir. Birincisi, orta şiddetli dört bozulmanın her birinde Macro-F1, temiz koşuldaki %25 veri düzeyinin (%62,6) altında kalmıştır. İkincisi, orta şiddetli Gauss gürültüsünde Macro-F1 (%44,1) temiz koşuldaki %10 düzeyinin (%48,7) de altına inmiştir. Bu ifadeler betimseldir, nedensel eşdeğerlik göstermez ve tanımlanan sentetik bozulma koşullarıyla sınırlıdır. Kuşatma kararlarının bootstrap kararlılığı ayrıca hesaplanmıştır (Tablo 8, son sütun). Yukarıdaki iki ifade kararlıdır: kuşatma kararlılığı, orta şiddetli Gauss gürültüsünün temiz %10 düzeyinin altında kalması için tekrarların %99,0'ı, dört orta şiddetli koşulun temiz %25 düzeyinin altında kalması için ise tekrarların en az %99,9'udur. Buna karşılık daha ince kuşatma etiketlerinin bir kısmı kararsızdır; şiddet 1'deki Gauss gürültüsü (%52,6) ve şiddet 3'teki Gauss bulanıklığı (%75,4) bu nedenle iki komşu aralık arasında sınırda değerlendirilmelidir.

Tablo 8. Bozulmuş koşulların temiz öğrenme eğrisindeki karşılığı (tam veri modeli, enterpolasyonsuz). Temiz eğri: %10'da %48,7; %25'te %62,6; %50'de %67,4; %100'de %74,4. Kararlılık sütunu, kuşatma kararının bootstrap tekrarlarındaki payıdır.

Koşul	Macro-F1	Temiz eğride karşılığı	Kararlılık
Gauss gürültüsü, şiddet 5	%21,2	< temiz %10	1,00
Gauss bulanıklığı, şiddet 5	%29,5	< temiz %10	1,00
Pikselleşme, şiddet 5	%31,8	< temiz %10	1,00
JPEG, şiddet 5	%37,7	< temiz %10	1,00
Gauss gürültüsü, şiddet 3	%44,1	< temiz %10	0,99
Gauss bulanıklığı, şiddet 3	%50,1	%10 – %25 arası	0,75
JPEG, şiddet 3	%53,3	%10 – %25 arası	0,99
Pikselleşme, şiddet 3	%57,1	%10 – %25 arası	1,00
JPEG, şiddet 1	%60,1	%10 – %25 arası	0,94
Gauss gürültüsü, şiddet 1	%62,5	%10 – %25 arası	0,53
Pikselleşme, şiddet 1	%65,0	%25 – %50 arası	0,85
Gauss bulanıklığı, şiddet 1	%70,6	%50 – %100 arası	0,99

3.9. Çekim grubu duyarlılık analizi

Tam dosya kopyası bulunmamıştır. Algısal hash tabanlı katı yakın kopya taraması 25 çift üretmiş, bunların 16'sı farklı katlara düşmüştür; ancak bu 16 çiftin hiçbiri aynı örneğe ait görünmemektedir. Yedisi farklı hastalık sınıfları arasındadır ve dolayısıyla aynı yaprağın iki karesi olamaz; tamamında ConvNeXt-Tiny gömü kosinüs benzerliği 0,41–0,84 aralığında olup yakın kopya eşiği 0,965'in belirgin biçimde altındadır; çekim zamanları arasındaki fark en az 55 saniye, ortanca 896 saniye ve en fazla 7,8 gündür. Bu çiftlerin, beyaz zemin çekim düzeneğinin sabit kadraj ve neredeyse değişmeyen arka planı nedeniyle oluşan algısal hash yanlış pozitifleri olduğu değerlendirilmiştir. Gerçek seri çekim kopyaları — 2–3 saniye arayla çekilmiş, ardışık dosya adlı ve gömü benzerliği 0,78–0,93 olan tarla görüntüleri — EXIF tabanlı gruplama ile aynı kata yerleştirilmiştir. Çekim ortamları arası eşleşmeler karşılıklı en yakın komşu ile tarandığında en yüksek benzerlikli adaylarda Hamming mesafesi 30–34 ve kosinüs benzerliği 0,58–0,60 bulunmuştur; bu değerler 64 bitlik hash için ilgisiz görüntü çiftlerinde beklenen düzeydedir (yaklaşık 32). Dolayısıyla aynı yaprağın iki çekim ortamındaki eşleşmiş sürümlerinin bulunmadığı değerlendirilmiştir.

On saniyelik pencere, önceden tanımlanan grup düzeyinde ayrımı korumuştur. Bununla birlikte pencere genişletildiğinde grup yapısı belirgin biçimde değişmektedir: 15 saniyede grup sayısı 946'dan 747'ye, 30 saniyede 527'ye düşmekte ve mevcut bölmede 15 saniye içinde çekilmiş 164, 30 saniye içinde çekilmiş 347 görüntü çifti farklı katlara dağılmaktadır. Bu yapısal bulgu, artık zamansal bağımlılık olasılığına işaret etmektedir. Duyarlılığın 15 ve 30 saniyelik pencerelerle sınırlandırılması bilinçlidir:

60 ve 120 saniyede grup sayısı 350 ve 214'e, en büyük grup ise 77 ve 121 görüntüye çıkmakta, yani gruplar artık bir çekim oturumunu değil neredeyse bütün bir çekim gününü temsil etmeye başlamaktadır. Söz konusu bağımlılığın performans üzerindeki etkisi ise bu çalışmada nicelenememiştir. Mevcut tahminler üzerinde yapılan bir keşifsel karşılaştırmada, 15 saniyelik pencerede komşusu farklı katta bulunan test görüntülerinin doğruluğu (n = 297, %88,2) komşusu aynı katta bulunanlardan (n = 275, %75,6) yüksek çıkmıştır (fark 12,6 yüzde puan; %95 GA 5,1–20,1). Ancak bu fark eğitim maruziyetine atfedilememektedir. Farklı katta komşusu bulunan 297 görüntünün 242'sinde komşu eğitim kümesinde, 55'inde yalnızca doğrulama kümesindedir; bu iki alt küme arasındaki doğruluk farkı 1,2 yüzde puandır ve güven aralığı sıfırı içermektedir (%88,4 ve %87,3; fark %95 GA −8,1 ile +12,0). Komşusu gradyan güncellemelerinde kullanılmayıp yalnızca doğrulama kümesinde bulunan alt kümenin de benzer başarı göstermesi, farkın grupların başlangıç zorluğu, çekim günü ve oturum bileşimi gibi başka etkenlerle açıklanabileceğine işaret eder. Öte yandan bu güven aralığı geniştir (n = 55) ve bir denklik testi değildir; dolayısıyla eğitim maruziyetinin katkısı ne gösterilmiş ne de dışlanmıştır. Seri çekim ile izole çekim arasındaki fark da ayırt edilememiştir (6,2 yüzde puan; %95 GA −1,2 ile +13,3). Zamansal bağımlılığın nedensel etkisini ölçmek için 15 veya 30 saniyelik pencereyle ya da doğrulanmış yaprak kimliğine dayanan bir bölmeyle yeniden eğitim gerekmektedir; bu, çalışmanın açık bir sınırlılığıdır.

3.10. Tartışma

Bulgular, saha koşullarındaki performans açığının tek bir nedene indirgenemeyeceğini göstermektedir. En aktarılabilir sonuç, bozulma maliyetinin eğitim verisi cinsinden ifade edilmesidir: orta şiddetli dört bozulmanın her birinde Macro-F1'in temiz koşuldaki %25 veri düzeyinin altında kalması, veri toplamaya yapılan yatırımın ancak çekim kalitesi belirli bir eşiğin üzerinde tutulduğunda geri döndüğünü göstermektedir. Bu, Barbedo'nun (2018b) veri kümesi büyüklüğünün belirleyiciliğine ilişkin bulgusunu tamamlayıcı niteliktedir: veri miktarı gerçekten belirleyicidir, fakat görüntü kalitesi düştüğünde bu belirleyicilik kısmen tükenmektedir. Karşılaştırmanın tanımlanan sentetik bozulma koşullarına ait olduğu ve bu şiddetlerin gerçek sahada görülme sıklığının ölçülmediği vurgulanmalıdır. Bozulmaların operasyonel ayrımı yönlendirici olmalıdır. Çözünürlük ve sıkıştırma kalitesi çekim anında doğrudan seçilebilir; bulanıklık yeniden çekim, odaklama ve kamerayı sabitleme ile kısmen denetlenebilir; arka plan karmaşıklığı ise saha koşullarında büyük ölçüde denetlenemez. Düşük şiddette en büyük kaybın JPEG sıkıştırmasında ve gürültüde görülmesi, doğrudan seçilebilen bu etkenlerin saha uygulamalarında öncelikli olduğunu göstermektedir. Pikselleşmenin tarla görüntülerinde belirgin biçimde daha yıkıcı olması bu önceliği güçlendirmektedir: mobil uygulamalarda görüntü küçültmenin, kontrollü çekimlerdeki etkisinden çok daha büyük bir maliyeti vardır.

Çekim ortamı farkına ilişkin bulgu, Noyan'ın (2022) PlantVillage'daki arka plan yanlılığına dair sonucuyla aynı yönde ancak farklı bir mekanizmaya işaret etmektedir; bu çalışmada arka plan, etiketle ilişkilenen bir kısayol olarak değil tam veri koşulunda kısmen telafi edilebilen bir alan farkı olarak davranmaktadır. Ancak veri setinin çekim yapısı gereği ortam, tarih ve oturumla iç içe geçtiği için bu ayrımın nedensel olarak sınanması mevcut veriyle mümkün değildir. Son olarak, referans başarı düzeyinin açıkça hesaplanması ağır bozulma sonuçlarının yorumunu değiştirmiştir: mutlak kayıpların düşük veri koşulunda daralması ilk bakışta dayanıklılık izlenimi vermekte, oysa başarı referans düzeye indiğinde kaybedilebilecek performans kalmadığından bu daralma beklenen bir sonuçtur. Dayanıklılık çalışmalarında referans düzeyin hesaplanıp raporlanması bu nedenle gereklidir.

3.11. Sınırlılıklar

Sonuçlar yalnızca ImageNet ön eğitimli ConvNeXt-Tiny mimarisi için geçerlidir. Veri setinde sağlıklı sınıf bulunmadığından görev hastalık tespiti değil beş hastalık arasında sınıflandırmadır ve kaynak hastalık etiketleri bağımsız bir bitki patoloğu tarafından yeniden doğrulanmamıştır. Tarla ile beyaz zemin arasındaki fark nedensel bir arka plan etkisi değildir; çekim ortamı tarih ve diğer edinim koşullarıyla iç içe geçmiştir. Sınıf ile çekim tarihi arasındaki ilişki de sınıf bazındaki farkların bir kısmının oturum bileşiminden kaynaklanabileceği anlamına gelir.

Her kat için belirlenmiş tohum kullanılmış, ancak aynı bölme farklı eğitim tohumlarıyla tekrarlanmamıştır; dolayısıyla eğitim varyansı ölçülmemiştir. Bootstrap güven aralıkları test örnekleme belirsizliğini ölçmekte, eğitim ve optimizasyon belirsizliğini kapsamamaktadır. Tam veri koşulunda katlar arası temiz Macro-F1 yayılımı %68,9 ile %80,3 arasındadır (standart sapma 4,8) ve bootstrap güven aralığının yarı genişliğinden büyüktür; bu nedenle bütün değerler tek ondalığa yuvarlanmıştır. Her veri düzeyinde aynı epoch tavanı ve erken durdurma reçetesi kullanıldığından, küçük alt kümelerde

toplam optimizasyon adımı da daha azdır; veri azlığı sonucu, benzersiz görüntü sayısının aynı reçete altında azaltılmasının toplam etkisidir. Doğrulama kümesi bütün düzeylerde sabit tutulduğu için model seçimi verisi kıtlığı incelenmemiştir.

Letterbox dolgusu nedeniyle yaprağın etkin çözünürlüğü 224 pikselin belirgin biçimde altındadır; düz dolgu bantları özellikle JPEG sıkıştırmasının gözlenen maliyetini azaltabilir (Şekil 1). Bu nedenle sonuçlar, bütün kadrajı doğal görüntüyle dolu ImageNet-C örnekleriyle doğrudan eşdeğer kabul edilmemelidir. Uzun ve ince bir nesnenin kareye letterbox'lanması girdinin önemli bir bölümünü harcamaktadır; daha sıkı bir kırpma veya kare olmayan bir girdi boyutu gelecek çalışmalarda değerlendirilmelidir. Şiddet 5 koşulları bir stres testidir ve bu şiddetlerin sahada görülme sıklığı ölçülmemiştir. Shapley koalisyonlarında bozulmalar sabit sırada uygulanmış olup sonuçlar bu zincire aittir. Son olarak, Bölüm 3.9'da belirtildiği üzere daha geniş çekim grubu pencerelerinde artık zamansal bağımlılık olasılığı dışlanamamıştır; bu bağımlılığın performansa etkisi yeniden eğitim yapılmadığı için nicelenememiştir.

4. SONUÇ VE ÖNERİLER

Bu çalışmada, beş çeltik yaprak hastalığı üzerinde tek bir mimariyle, eğitim verisi azlığı ve dört sentetik görüntü bozulmasının tekil ve birleşik etkileri çekim grubuna duyarlı bir protokol altında nicelenmiştir. Tam eğitim verisiyle temiz Macro-F1 %74,4 ölçülmüş; eğitim verisinin %10'a indirilmesi 25,7 yüzde puan kayba yol açmıştır. Ağır Gauss gürültüsü başarıyı referans düzeye indirmiş, beyaz zeminli ve tarla çekimleri arasında tam veride 12,5 yüzde puanlık gözlemsel alan farkı bulunmuştur. Düşük ve orta şiddetli çözünürlük kaybı tarla görüntülerinde 20–25 yüzde puan daha maliyetli olmuştur. Birleşik 53,6 puanlık kaybın %29,7'si Gauss gürültüsüne, %24,3'ü veri azlığına atfedilmiştir. En aktarılabilir sonuç, orta şiddetli dört bozulmanın her birinde Macro-F1'in temiz koşuldaki %25 veri düzeyinin altında kalması, orta şiddetli Gauss gürültüsünde ise %10 düzeyinin de altına inmesidir. Tanımlanan bozulma koşulları altında, saha uygulamalarında çekim kalitesinin standartlaştırılması ek veri toplamakla karşılaştırılabilir bir öncelik olarak görünmektedir.

Bu bulgular ışığında şu öneriler getirilmektedir. Saha uygulamalarında görüntüler mümkün olan en yüksek çözünürlükte ve düşük sıkıştırma oranıyla kaydedilmeli, mobil uygulamalarda görüntü küçültme işleminden kaçınılmalı, bulanıklık ise yeniden çekim, odaklama ve kameranın sabitlenmesiyle denetlenmelidir. Veri toplama çalışmalarında iki çekim ortamının aynı günlerde birlikte kullanılması, sınıfların çekim günlerine dengeli dağıtılması ve hastalık etiketlerinin bağımsız bir bitki patoloğu tarafından doğrulanması, bu çalışmada nedensel olarak sınanamayan çekim ortamı etkisinin ayrıştırılmasını mümkün kılacaktır. Gelecek çalışmalarda sonuçların farklı mimarilerde ve farklı eğitim tohumlarıyla sınanması, 15 veya 30 saniyelik çekim grubu pencereleriyle ya da doğrulanmış yaprak kimliğine dayanan bir bölmeyle yeniden eğitim yapılması, letterbox yerine daha sıkı kırpma veya kare olmayan girdi boyutlarının değerlendirilmesi ve sentetik bozulma şiddetlerinin gerçek saha görüntülerinde görülme sıklığının ölçülmesi önerilmektedir.

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ARTIFICIAL BORDERS AND FRAGMENTED NATIONS: COLONIAL STATE-MAKING AND IDENTITY POLITICS IN THE LEVANT

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ABSTRACT
The political landscape of the Levant continues to reflect the enduring legacies of colonial state-making and territorial reconfiguration. This paper examines how British and French mandate policies transformed the post-Ottoman Levant by creating new political boundaries and institutional arrangements that reshaped patterns of identity and governance. It argues that colonial state-building institutionalized sectarian, ethnic, and religious divisions within newly established states, contributing to fragmented national identities and contested statehood.
Using a comparative historical approach informed by constructivist and postcolonial perspectives, the study analyzes the impact of the Sykes–Picot Agreement, the San Remo Conference, and the League of Nations Mandate system on the formation of Lebanon, Syria, Palestine, and Transjordan. The paper further explores how these colonial legacies continue to influence contemporary debates on citizenship, political representation, sovereignty, and conflict in the Levant.
By linking colonial border-making with contemporary identity politics, the study contributes to broader discussions on nationalism, state-building, and postcolonial governance, highlighting the lasting influence of colonial institutions on the region's political and social landscape.
Keywords: Levant; Colonial State-Making; Identity Politics; Artificial Borders; Nationalism; British and French Mandates; Postcolonial Governance.

INTRODUCTION
The political map of the contemporary Levant is generally understood through the territorial states of Lebanon, Syria, Palestine and Jordan. Yet this territorial order is relatively recent. For centuries, the region existed within political arrangements that did not correspond neatly to the modern nation-state. Under Ottoman rule, political belonging was usually layered, has involved religious community, locality, tribe, region and imperial affiliation at the same time. These identities could overlap rather than exist as mutually exclusive categories. The collapse of the Ottoman Empire after the First World War introduced a very different political framework in which territorial boundaries, centralized administration and national sovereignty became increasingly important. The transition from Ottoman imperial space to the territorial states of the modern Levant therefore involved not only a redistribution of territory but also a transformation in the political meaning of belonging. This transformation became particularly significant with the establishment of British and French mandates across the former Ottoman Arab provinces. Syria, Lebanon, Palestine and Transjordan were placed within a new political and administrative order under the League of Nations mandate system. British and French authorities introduced administrative structures, territorial boundaries and political institutions that increasingly organized populations within clearly defined territorial units. The significance of this process lies not simply in European control over the region, but in the ways colonial administration contributed to the institutionalization of new forms of political authority. The territorial state gradually became the principal framework through which questions of citizenship, political representation and national belonging were negotiated (Tejel & Öztan, 2022).
The Sykes–Picot Agreement of 1916 occupies an important place in explanations of this transformation. It is frequently presented as the moment when Britain and France divided the Middle East into artificial states. Although the agreement reflected imperial ambitions and influenced the subsequent territorial settlement, the modern borders of the Levant were not simply produced by Sykes–Picot. They emerged through a longer process involving wartime arrangements, military occupation, the San Remo Conference, the League of Nations mandates, diplomatic negotiations and interactions with local political actors. Recent scholarship on Middle Eastern borderlands has consequently questioned the conventional image of Europeans simply drawing lines across a passive region. Border-making was a contested process in which colonial authorities and local actors interacted, negotiated and resisted, while older patterns of movement and affiliation continued to cross the emerging boundaries (Tejel & Öztan,

2022). This observation is important because describing the borders as "artificial" can itself create an overly simple picture of the region. It may suggest that the Levant was previously composed of naturally unified communities that were subsequently divided by European powers. The historical reality was considerably more complex. Ottoman society contained multiple and overlapping forms of belonging, and religious, tribal, linguistic, economic and regional affiliations frequently extended across administrative boundaries. The issue, therefore, is not simply whether colonial powers created identities that did not previously exist. A more useful question is how colonial state-making changed the political significance of identities that already existed.

Identity does not automatically become political simply because a community possesses a particular religious, ethnic or cultural affiliation. It becomes politically significant when institutions, territorial boundaries, political competition and struggles over state power give it political meaning. This understanding is consistent with constructivist approaches, which regard identity as historically produced and continuously reconstructed rather than as a fixed or natural category. Anderson's (1983) concept of the nation as an "imagined community" demonstrates how national belonging can emerge among people who may never encounter most of their fellow citizens. Gellner (1983), similarly, connected the development of nationalism with the emergence of modern territorial states and the social conditions necessary for national integration. These approaches provide a useful basis for examining how the creation of new territorial states in the Levant affected older forms of communal belonging. Colonial governance played an important role in this transformation because European administrations encountered societies in which identities already existed in overlapping forms and attempted to govern them through new territorial and institutional arrangements. Benjamin White's work on French Mandate Syria, for example, demonstrates how the categories of "majority" and "minority" acquired new political significance within the emerging nation-state. The communities themselves were not colonial inventions; rather, their political status and relationship to the state were transformed by the new territorial and administrative order (White, 2011). This distinction is central to understanding colonial identity politics. Colonialism did not necessarily invent communal identities, but it could classify, reorganize and institutionalize them in ways that altered their political importance.

Similar processes developed differently across the Levant. In Lebanon, the creation and consolidation of Greater Lebanon brought different territories and communities into a new political framework in which communal representation became increasingly important. In Syria, French administrative policies interacted with the development of Syrian and Arab nationalisms. Palestine developed within a particularly contested political environment in which British mandate rule intersected with competing Jewish and Palestinian national projects. Transjordan followed a different trajectory, combining British influence, Hashemite rule, tribal structures and territorial state-building. These cases therefore cannot be reduced to one uniform model of colonial rule. What connects them is the broader shift from imperial forms of political organization towards territorial states in which questions of nationality and citizenship acquired increasing importance. The creation of borders also did not immediately eliminate older forms of mobility and interaction. Borderlands remained spaces through which people, goods and political ideas moved, often challenging the attempts of new states to establish clear territorial control. This has encouraged scholars to move beyond the idea of borders as fixed lines and to examine them as institutions that were continuously negotiated and contested (Tejel & Öztan, 2022). Such an approach also brings local agency into the analysis. Colonial administrations possessed considerable power to establish institutions and territorial arrangements, but local political movements, elites, communities and individuals responded to these changes in different ways. They accepted, challenged and sometimes reproduced colonial structures according to their own political interests.

The legacy of these processes did not end with independence. The emerging postcolonial states inherited many of the territorial boundaries and institutional arrangements developed during the mandate period, while simultaneously attempting to construct their own national identities. In some cases, communal identities became incorporated into political institutions; in others, governments sought to suppress or transcend communal divisions through centralized nationalism. The result was not a single pattern of identity politics but a range of competing relationships between state, nation and community. A substantial body of scholarship has examined these questions from different perspectives. Historians have studied the collapse of the Ottoman Empire and the mandate system; scholars of nationalism have explored the development of Arab, Syrian, Lebanese and Palestinian national identities; and research on sectarianism has examined communal politics, particularly in Lebanon. Postcolonial scholarship has

further highlighted the relationship between imperial power, knowledge and territorial organization. More recent borderlands research has questioned the idea that colonial borders were simply imposed upon passive populations and has emphasized mobility, negotiation and local agency. Despite this extensive scholarship, the relationship between colonial territorialization, institutionalization and identity formation remains insufficiently integrated into a single comparative framework.

This constitutes the central research gap addressed by this paper. Existing approaches often examine colonial borders, state formation and identity politics as closely related but analytically separate processes. Less attention has been given to the mechanism through which territorial reorganization altered the political significance of existing identities and embedded them within new state institutions. The paper therefore moves beyond the question of whether colonial powers "created" artificial states and instead asks how colonial state-making transformed political space and reshaped the relationship between community and state. The paper examines Lebanon, Syria, Palestine and Transjordan comparatively to explore this transformation. It argues that colonial state-making did not simply divide a previously unified Levant through artificial borders. Rather, it territorialized political space, reorganized existing patterns of belonging and institutionalized particular identities within emerging states. These processes contributed to competing national projects whose effects continued into the postcolonial period.

At the same time, the paper does not treat colonialism as a complete explanation for contemporary identity politics. The later trajectories of the Levant were also shaped by postcolonial governments, nationalist movements, regional interventions, wars, migration and local political struggles. Colonial borders provided an institutional and territorial framework, but their political consequences were continuously reshaped by actors within and beyond the state. Understanding contemporary identity politics therefore requires attention to both historical structures and political agency. The central concern of this study is consequently not simply where the borders of the Levant came from, but what those borders came to mean politically. Once territorial boundaries became associated with citizenship, representation and national sovereignty, they also influenced how communities negotiated their place within the state. The transition from Ottoman imperial space to the postcolonial territorial state thus transformed not only geography but also the political language of belonging. Examining this transformation provides a way of understanding why national identity in the Levant has remained contested and why communal, territorial and transnational identities continue to intersect within the region's political life.

THEORITICAL FRAMEWORK AND RESEARCH GAP

Understanding identity politics in the Levant requires moving beyond the idea that identities are fixed characteristics carried by communities across time. Religious, ethnic, linguistic and regional identities have historical roots, but their political significance can change with changing political institutions. A community may understand itself through religion, locality or imperial affiliation in one political context and articulate similar attachments in national or territorial terms in another. The transition from Ottoman imperial rule to colonial and postcolonial territorial states therefore provides an important context for examining how identities acquired new political meanings.

The paper primarily draws on a constructivist understanding of identity. From this perspective, identities develop through historical and political interaction rather than existing as completely fixed categories. Wendt (1992) similarly argues that political identities and interests are shaped through interaction. Applied to the Levant, this approach suggests that the creation of new territorial states did not automatically produce new identities, but created political conditions in which questions of citizenship, representation and belonging acquired greater importance. It also challenges primordial explanations that treat sectarian, ethnic or religious identities as naturally destined to become political. Identity becomes politically significant when institutions and political struggles connect it to power, recognition and representation. Theories of nationalism provide a second part of the framework. Anderson's (1983) concept of the nation as an imagined community helps explain how populations can develop a sense of belonging to a wider territorial community. Gellner (1983) further connects nationalism with the institutions of modern political organization, drawing attention to the relationship between national identity and the territorial state. Smith's (1986) ethno-symbolist perspective adds that modern national identities can draw upon older memories, symbols and cultural communities. Taken together, these approaches allow the paper to recognize both the historical depth of identity and its changing political

expression. National identities in the Levant did not emerge from nothing, but neither were their modern political forms simply inherited unchanged from the past.

A postcolonial perspective further shifts attention towards the role of colonial power in organizing territory and political knowledge. Colonial administrations did not govern populations that were already organized as modern nations; they participated in defining territories, administrative categories and political institutions. Said's (1978) work is useful here because it demonstrates the relationship between systems of knowledge and structures of power. Yet colonialism should not be understood as having invented all communal differences. White's (2011) study of French Mandate Syria demonstrates instead how existing communal distinctions acquired new political significance when incorporated into the territorial nation-state. The colonial state could therefore transform social difference into an institutional and political category without creating that difference in the first place. Historical institutionalism complements this argument by drawing attention to the persistence of institutions after their original creation. Colonial boundaries, administrative arrangements and political practices did not disappear with independence; postcolonial governments inherited and adapted many of them. This does not imply that colonial institutions determined later political outcomes, but that they created institutional paths within which subsequent political actors operated.

These perspectives together suggest that a border should not be understood merely as a geographical line. Once institutionalized, a border can determine jurisdiction, citizenship and political membership, thereby influencing how territorial belonging is understood. At the same time, borders never completely eliminated older forms of mobility and cross-border affiliation. Religious, tribal, economic and political networks continued to connect populations across the new states. The tension between territorial statehood and continuing forms of cross-border belonging is therefore central to understanding identity politics in the Levant. The research gap addressed by this paper lies in bringing these processes together. Existing scholarship has extensively examined colonialism, nationalism, sectarianism and border formation, but these dimensions are often analyzed separately. Less attention has been given to how territorial reorganization changed the political environment in which existing identities operated and how those identities became institutionalized within emerging states. The paper therefore shifts attention from the border itself to the political consequences of territorialization. This approach also avoids both colonial and cultural determinism. Contemporary fragmentation cannot be explained entirely through European border-making, but neither can it be reduced to supposedly ancient and inevitable communal divisions. Instead, identity formation is understood here as an interaction between historical identities, colonial institutions, territorial boundaries and local political agency.

The theoretical contribution of the paper lies in connecting territorialization, institutionalization and identity formation. Territorialization created new political spaces; institutions gave those spaces political meaning; and identities were subsequently negotiated within them. The national identities that emerged were therefore neither simply imposed by colonial powers nor entirely inherited from the past. They developed through the interaction between colonial structures and local agency. This framework provides the basis for the comparative analysis of Lebanon, Syria, Palestine and Transjordan that follows.

FROM OTTOMAN IMPERIAL SPACE TO COLONIAL TERRITORIAL ORDER

The transition from Ottoman rule to the mandate system is often described as a straightforward movement from empire to nation-state. In reality, the transformation was neither immediate nor complete. What changed after the First World War was not simply who governed the region, but the political logic through which territory and authority were organized. The Ottoman Empire had certainly developed territorial administration, provincial boundaries and systems of central control, particularly during the nineteenth-century reforms. Yet political belonging within the empire was not based exclusively on membership in a territorially bounded nation. Local, religious, familial, tribal and regional affiliations existed alongside an attachment to the Ottoman state. The political geography of the region was consequently more layered than the later nation-state framework would suggest.

This does not mean that Ottoman rule was a borderless or completely decentralized system. The empire was divided into provinces and districts, and the central government increasingly attempted to strengthen administrative control during the nineteenth century. The reorganization of the Arab provinces produced new administrative units, including the provinces of Damascus, Aleppo and later Beirut, while local elites continued to play an important role in governance. In Greater Syria, the relationship between

Istanbul and provincial society was frequently negotiated rather than simply imposed. Local notables, provincial officials and communities could exercise considerable influence over how imperial policies were implemented. Abu-Husayn's (1992) study of the Sidon-Beirut region, for instance, demonstrates the extent to which Ottoman authorities adapted administrative practice to local circumstances rather than applying a completely uniform model of provincial governance. The distinction is important because it reminds us that the Ottoman political order itself was changing and that the transition to the territorial state did not begin from an entirely fixed or static imperial system. The nineteenth century consequently witnessed a gradual transformation in the relationship between territory and political authority. Ottoman reforms sought greater administrative centralization, clearer provincial organization and more direct state control. These developments introduced elements of territorial governance that would later become important under the mandate system. Yet the empire continued to accommodate multiple forms of belonging. In the Arab provinces, political life remained shaped by local elites, religious communities, tribal networks and commercial connections that did not always correspond to administrative boundaries. The experience of Beirut illustrates this complexity. As the city expanded economically during the nineteenth century, its political and commercial relationship with its surrounding hinterland generated new demands for administrative reorganization. The eventual creation of the province of Beirut in 1888 was itself the result of political struggles over how Ottoman administrative space should be organized (Hanssen, 2005). The history of borders in the Levant, therefore, did not begin with European colonialism; rather, colonial rule entered a region in which the relationship between territory, authority and community was already being renegotiated.

What distinguished the post-First World War settlement was the increasing dominance of a different principle: political authority was to be organized through territorially bounded states. The collapse of Ottoman sovereignty created a political opening in which competing projects of political order emerged. Arab nationalist movements had articulated demands for independence, while Britain and France pursued their own strategic interests in the former Ottoman territories. The result was not a simple replacement of one political system with another, but a struggle over what the political future of the region would look like. The Sykes–Picot Agreement of 1916 is central to this history, although its significance needs to be treated carefully. The agreement reflected British and French wartime negotiations over spheres of influence in the Arab provinces of the Ottoman Empire. It is frequently remembered as the document that "created" the borders of the modern Middle East. Historically, however, its role was more complicated. The agreement was not a final blueprint that was simply implemented after the war. Subsequent diplomatic negotiations, military developments, nationalist resistance and international arrangements altered the territorial settlement considerably. Donaldson (2023) therefore argues that while Sykes–Picot was important in shaping the political conditions of the post-war settlement, it was not ultimately decisive in determining the final political map. Its importance lies as much in what it represented the territorial ambitions of late imperial powers as in the precise lines it proposed.

The post-war settlement gradually transformed these competing ambitions into a new international and territorial order. At San Remo in 1920, the Allied powers agreed upon the allocation of mandates, with France receiving authority over Syria and Lebanon and Britain receiving authority over Palestine and Mesopotamia. The League of Nations subsequently formalized these arrangements. The language of the mandate system presented colonial administration as a temporary form of tutelage intended to prepare territories for self-government. In practice, however, the mandate system established European political authority over territories whose populations had already developed their own aspirations concerning independence and political representation. The mandate period thus became a crucial stage in the consolidation of territorial states across the post-Ottoman Levant. The transformation can be understood as a process of re-spatialization. The region that had previously been connected through imperial institutions and overlapping social networks was increasingly divided into territories in which separate state authorities claimed jurisdiction. Murray-Miller (2022) describes this broader transformation as the emergence of a new geopolitical landscape of bounded territories and states following the collapse of the Ottoman Empire. What changed was therefore not simply the location of a boundary. The meaning of territory itself changed: it became increasingly connected to sovereignty, administration, citizenship and national political claims.

This process can be seen particularly clearly in the case of Syria. French authorities did not simply inherit an already consolidated Syrian state. They had to construct administrative and political

institutions within a territory whose boundaries and internal political organization were themselves contested. The French experimented with different administrative arrangements, including separate political entities, while simultaneously confronting demands for Syrian independence. The development of a Syrian constitutional order during the mandate illustrates the gradual movement from an administrative arrangement towards a more recognizably national political order. Mestyan (2021) shows how the creation of the Syrian constitution in 1928 reflected the transformation of mandate administration into a political order in which questions of sovereignty and national representation became increasingly important. The importance of this transformation becomes even clearer when examining the relationship between borders and minority identities. Under the emerging nation-state system, a community could increasingly find itself on one side of a political border while members of the same broader social or ethnic group lived on the other. The Kurdish case illustrates this particularly well. The post-Ottoman borders divided Kurdish populations across several new territorial jurisdictions. White (2011) demonstrates that the establishment of the Syrian-Turkish border did not merely separate territories; it also contributed to the political "mineralization" of Kurds living within Syria. A population that had previously existed within an imperial political framework was now increasingly positioned in relation to a national majority and minority structure.

This is where the relationship between border formation and identity becomes particularly important. The border did not create Kurdish identity. Nor did it automatically create a Syrian national identity. What it did was change the political environment in which both identities operated. Once a territorial state claimed authority over a particular population, the question of who belonged to that state acquired greater political importance. Identity could now become connected to citizenship, representation and territorial loyalty. In other words, territorialization did not simply divide existing communities; it changed the political consequences of belonging to those communities. Lebanon followed another trajectory. The territory that became Greater Lebanon was shaped by Ottoman administrative changes as well as European intervention, and the establishment of the French Mandate placed these territories within a new political framework. The historical development of Mount Lebanon itself demonstrates that communal and territorial arrangements had already been politicized before the First World War. The creation of the Mutasarrifate in 1861, for example, produced a distinctive administrative system involving communal representation. This was not simply a French invention imposed after 1918. Rather, it reflected an earlier interaction between Ottoman authorities, European powers and local political actors. The mandate period subsequently built upon and transformed these earlier arrangements.

This history complicates any straightforward argument that colonialism created sectarian politics in Lebanon. Communal identities and forms of representation existed before the mandate. What changed was their relationship to the territorial state. Greater Lebanon incorporated communities and territories into a political unit whose legitimacy and boundaries became subjects of intense political debate. Communal identity increasingly became connected to questions concerning access to political power and the character of the new state. The colonial period therefore contributed to the institutionalization of political differences that had older historical roots.

Palestine presents an even more complex transformation. British rule established a mandate framework in which competing political projects concerning the territory developed under the same colonial authority. The Balfour Declaration and its incorporation into the Palestine Mandate created a particularly difficult political environment in which British commitments, Zionist aspirations and Palestinian demands for self-determination interacted and increasingly conflicted. The significance of the mandate was therefore not simply that it established another territorial administration. It provided the institutional setting in which competing claims concerning territory, population and political sovereignty became increasingly organized as national claims. The subsequent history of Palestine demonstrates how territorialization can intensify rather than resolve competing conceptions of political community.

Transjordan developed through a somewhat different combination of imperial and local political forces. British involvement, Hashemite state-building and existing tribal and regional networks contributed to the consolidation of a territorial political unit. Here too, the emergence of a state did not simply replace earlier forms of belonging with a single national identity. Instead, dynastic legitimacy, tribal affiliations, local identities and territorial nationalism became part of an evolving political order. The case demonstrates why colonial state-making should not be understood as a uniform process across the Levant. Different territories experienced different combinations of colonial administration, local political agency and pre-existing social structures. Across these cases, one pattern nevertheless becomes

visible. The mandate system progressively attached political authority to bounded territorial units. This produced a fundamental change in the relationship between state and society. Under the Ottoman Empire, a person's political position could be understood through several overlapping affiliations within an imperial framework. Under the emerging territorial states, those affiliations increasingly had to be negotiated in relation to a specific state territory. The question was no longer simply which community one belonged to, but also which state claimed authority over that community and how that community would be positioned within the political order.

The process was neither complete nor uncontested. Borders remained porous, and social networks continued to cross them. Tribal groups, merchants, refugees, religious communities and political activists often maintained connections across the new frontiers. Recent scholarship has shown that these movements were not marginal to the process of state formation; they were part of it. Borders were strengthened precisely because states encountered populations and networks that did not fit neatly within the territorial framework they were attempting to establish. The making of the border was therefore also a struggle over mobility, authority and political belonging. The transition from Ottoman imperial space to colonial territorial order should consequently not be understood as a simple movement from "unity" to "fragmentation." The Ottoman system itself contained divisions, hierarchies and administrative boundaries, while the post-Ottoman states developed new forms of political community and national consciousness that cannot be reduced to colonial imposition. The more significant transformation was that political differences increasingly became organized through territorial institutions. Communities that had previously existed within overlapping political and social spaces were now situated within states that claimed exclusive authority over defined territories.

This shift provides the historical foundation for understanding the later politicization of identity in the Levant. Colonial state-making created the territorial and institutional framework within which identities could acquire new political meanings, but it did not determine how those identities would subsequently develop. Local actors, nationalist movements and postcolonial governments continued to reshape the relationship between territory and belonging. The mandate period therefore represents neither the beginning of identity in the Levant nor the complete explanation for its contemporary politics. It represents a critical moment in which the relationship between territory, state authority and collective identity was fundamentally reorganized.

COLONIAL STATE MAKING AND THE TERRITORIALISATION OF IDENTITY

The creation of territorial states in the Levant did not follow a single pattern. British and French authorities governed different territories through different institutions, while local communities responded to colonial rule in different ways. Yet a broader transformation can be identified across Lebanon, Syria, Palestine and Transjordan: political authority increasingly became attached to bounded territories. This altered the relationship between existing forms of belonging and the emerging state. Religious, ethnic, regional and tribal identities did not disappear, but their political significance increasingly came to be negotiated within territorial states. Lebanon illustrates this transformation particularly clearly. Communal politics predated the French Mandate. The Ottoman creation of the Mount Lebanon Mutasarrifate in 1861 had already established a distinctive political arrangement in which communal representation played an important role. The creation of Greater Lebanon in 1920 nevertheless changed the political context by bringing Mount Lebanon together with surrounding territories and populations. The question consequently shifted from managing communities within an autonomous region to defining the political character of a new territorial state. Under the French Mandate, communal identities became increasingly connected to political representation and access to state institutions. Colonial rule therefore did not create Lebanese sectarian identities, but it contributed to embedding existing communal differences within a new territorial political framework (Makdisi, 2000).

Syria followed a different trajectory. French authorities experimented with differentiated administrative arrangements and separate political units, while nationalist movements increasingly demanded a unified and sovereign Syrian state. Rather than simply producing permanent fragmentation, colonial territorial policies also encouraged opposition to such divisions. The Syrian Revolt of 1925–27 demonstrated the growing importance of political mobilization that crossed communal and regional boundaries. Syrian nationalism consequently developed partly through resistance to colonial attempts to organize political space. At the same time, the emerging territorial state transformed the meaning of communal identities.

As White (2011) demonstrates, categories such as "majority" and "minority" acquired greater political significance within the new national framework. The Kurdish case further demonstrates how territorialization changed the political meaning of identity. Kurdish communities existed across Ottoman territories before the modern borders separating Turkey, Syria and other states were established. The borders did not create Kurdish identity, but they placed Kurdish populations under different national administrations. In Syria, Kurdish identity increasingly became connected to questions of citizenship, recognition and political rights within an Arab-oriented national framework. An existing identity was therefore given new political significance by the territorial state.

Palestine represents a particularly important case because the British Mandate became the setting for competing national projects. Zionist and Palestinian political movements increasingly articulated claims concerning territory, political representation and national self-determination. The Balfour Declaration and its incorporation into the mandate framework created an institutional environment in which these competing claims developed. Questions of immigration, land, demographic change and political authority became closely connected to competing definitions of national belonging. The Palestinian case consequently demonstrates how colonial governance could transform social differences into competing territorial claims rather than simply managing them. Transjordan developed through a different combination of British influence, Hashemite authority and local political structures. Tribal networks, local elites and dynastic legitimacy all contributed to the development of the territorial state. The case demonstrates that colonial state-making was not simply a process of external imposition. Local actors participated in constructing and negotiating the emerging political order, while territorial and non-territorial forms of belonging continued to coexist.

Despite these differences, the four cases reveal a common process. Colonial state-making increasingly connected political authority to territory. This can be understood as the territorialisation of identity: the process through which existing forms of belonging acquired new political meaning because they were incorporated into territorial institutions. Once the state became the principal framework of political authority, questions of citizenship, representation and sovereignty became closely connected to questions of identity. This did not mean that national identity replaced communal identity. Individuals could continue to identify simultaneously with religious, ethnic, tribal, regional, Arab and territorial communities. These identities could coexist, but they could also become politically competitive when access to state power or recognition was organized around particular categories. Identity politics therefore emerged not simply from social diversity but from the institutional organization of that diversity.

The postcolonial period further complicated this process. Newly independent states inherited colonial boundaries and institutions but modified them according to their own political projects. National governments, political elites and social movements reproduced, challenged and transformed these inherited structures. Colonialism therefore should not be treated as a complete explanation of contemporary identity politics. Its importance lies in the institutional and territorial framework it helped establish, within which later political actors developed their own understandings of citizenship, sovereignty and belonging. The experience of Lebanon, Syria, Palestine and Transjordan consequently suggests that colonial state-making did more than divide territory. It changed the political environment in which identities operated. Borders became connected to citizenship, territories to sovereignty and communal identities to political representation. The fragmented national projects of the contemporary Levant can therefore be understood not simply as the survival of ancient divisions, but as the outcome of an evolving interaction between inherited identities, colonial institutions and postcolonial political agency.

Colonial Institutions and the Politicization of Identity

The territorial reorganization of the Levant was accompanied by the development of institutions that gave political meaning to existing social differences. Borders alone could not produce identity politics. It was through administrative classification, citizenship practices, political representation and systems of governance that particular identities became increasingly relevant to access to political power and recognition. Colonial administrations frequently governed populations through categories such as community, minority and majority. These categories were not necessarily invented by colonial authorities, since religious and ethnic communities had long existed across the region. Their significance changed, however, when they became connected to territorial state institutions. In French Mandate

Syria, for example, communal distinctions became increasingly relevant to the organization of political authority. White (2011) demonstrates that the emergence of the category of the "minority" was closely connected to the development of the territorial nation-state. A community was no longer simply a religious or social group; it could now be positioned politically in relation to a national majority.

Lebanon demonstrates the institutionalization of this process even more clearly. Communal representation became an important principle of political organization, linking religious identity with access to state institutions. Although Lebanon's sectarian system developed through both pre-colonial and postcolonial processes, the mandate period contributed to placing communal representation within a territorial state framework. This helped make sectarian identity politically consequential rather than merely socially significant (Makdisi, 2000). Citizenship also became an important mechanism through which territorial states defined belonging. Under imperial rule, political membership had operated within a different framework, whereas the modern state increasingly required individuals to possess a formal relationship with a particular territory and government. This transformation created new distinctions between citizens, non-citizens and populations whose relationship with the state remained contested. Palestine provides the clearest example, where competing national claims made questions of citizenship, immigration and political representation deeply connected to competing definitions of belonging.

At the same time, colonial institutions did not determine political outcomes by themselves. Local elites, nationalist movements and communities actively negotiated these structures. Some sought greater representation through communal identities, while others promoted broader national identities that attempted to transcend them. Institutions therefore became arenas of political contestation rather than simply mechanisms of colonial control. The long-term significance of these arrangements lies in their institutional persistence. Independence transferred formal sovereignty to local governments, but many territorial and administrative structures remained. Postcolonial political actors consequently inherited institutions through which identity had already acquired political meaning. They could reform these institutions, but they also had incentives to reproduce them. Colonial state-making thus contributed to a path-dependent relationship between identity and political power in the Levant. The politicization of identity should therefore be understood as a process rather than a colonial invention. Existing identities became politically consequential when territorial institutions linked them to citizenship, representation and state power. This provides an important connection between colonial state-making and the identity politics that continued to shape the postcolonial Levant.

CONCLUSION

The transformation of the Levant from an Ottoman imperial space into a system of territorial states fundamentally altered the political relationship between territory and identity. British and French colonial rule did not simply create artificial borders or invent the identities that exist in the region today. Rather, colonial state-making reorganized political space and placed existing forms of belonging within new territorial and institutional frameworks. The experiences of Lebanon, Syria, Palestine and Transjordan demonstrate that this process produced different outcomes. Communal representation became institutionalized in Lebanon, colonial territorial divisions interacted with Syrian nationalism, competing national projects developed in Palestine, and dynastic, tribal and territorial identities interacted in Transjordan. These differences demonstrate that colonialism did not determine a single political trajectory.

What it did provide was a new framework in which identity became increasingly connected to citizenship, territory, representation and sovereignty. Postcolonial governments and political movements subsequently reproduced, challenged and transformed these arrangements. Contemporary identity politics in the Levant is therefore neither simply a survival of ancient communal divisions nor an uncomplicated consequence of colonial borders. It is the outcome of a continuing interaction between historical identities, territorial institutions and political agency. The concept of "artificial borders" is therefore useful only when understood critically. The central legacy of colonial state-making was not merely the lines drawn on maps, but the political institutions and competing national projects that developed around those lines. Examining this relationship helps explain why questions of belonging, citizenship and national identity have remained contested across the Levant long after the formal end of colonial rule.

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HUMAN RIGHTS AND FOREIGN POLICY: BALANCING NATIONAL INTERESTS AND INTERNATIONAL HUMAN RIGHTS NORMS

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Abstract
Human rights have become an increasingly significant dimension of contemporary international relations and foreign policy. However, states frequently face a complex dilemma between fulfilling international human rights norms and protecting their national interests. This study examines the relationship between human rights and foreign policy, focusing on how states balance international human rights commitments with political, economic, security, and strategic interests. The research employs a qualitative approach based on the analysis of academic literature, international treaties, policy documents, reports of international organizations, and relevant scholarly studies. It explores the extent to which human rights considerations influence foreign-policy decision-making and examines the factors that encourage or constrain states in promoting human rights internationally. The study argues that although international human rights norms have become an important source of legitimacy and diplomatic influence, their application remains selective and is often shaped by geopolitical interests and power relations within the international system. States may support human rights principles when these principles complement their strategic objectives, while prioritizing sovereignty and national interests when the two come into conflict. The study concludes that a sustainable balance between national interests and international human rights norms requires consistent diplomatic engagement, stronger international institutions, greater accountability, and a rules-based international order. By examining this tension, the study contributes to the broader understanding of the role of human rights in contemporary foreign-policy practices and international relations.
Keywords: Human Rights; Foreign Policy; National Interests; International Human Rights Norms; International Relations; Diplomacy; State Sovereignty; International Law; Geopolitics; Global Governance

1. Introduction

Human rights occupy a central position in the contemporary international system. Although the protection of individual rights was historically regarded primarily as a matter falling within domestic jurisdiction, the development of international human-rights law after the Second World War transformed the relationship between states, individuals, and the international community. The adoption of the Universal Declaration of Human Rights (UDHR) by the United Nations General Assembly on 10 December 1948 represented a major turning point in this development. The Declaration established a common framework of fundamental rights and freedoms and subsequently influenced the development of numerous international human-rights treaties.

The internationalization of human rights has also affected foreign policy. States increasingly refer to human rights when establishing diplomatic relationships, providing development assistance, imposing sanctions, negotiating international agreements, participating in multilateral institutions, and responding to armed conflicts and humanitarian crises. Consequently, foreign policy can no longer be understood solely in terms of military capabilities, territorial security, economic interests, and the balance of power. Normative considerations, including human rights, international law, legitimacy, identity, and international reputation, have become important elements of foreign-policy analysis.

Nevertheless, the integration of human rights into foreign policy has created a persistent tension. States are expected to respect international human-rights norms, but governments also have responsibilities to protect national security, economic prosperity, political stability, territorial sovereignty, and strategic

interests. These objectives do not always coincide. A government may therefore face difficult choices when promoting human rights abroad could threaten an important economic relationship, undermine security cooperation, damage a strategic alliance, or increase the possibility of regional instability.

This tension is particularly important from an International Relations perspective. Realist approaches emphasize state survival, power, security, and national interest, whereas liberal and constructivist approaches provide greater space for international institutions, norms, identities, and ideas. The debate between these perspectives helps explain why states sometimes promote human rights strongly while, in other circumstances, remain reluctant to criticize serious violations by strategically important partners.

Recent scholarship in foreign-policy analysis demonstrates that human rights can influence foreign-policy instruments including sanctions, military intervention, foreign aid, and diplomatic engagement. It also emphasizes the role of non-state actors, civil society, NGOs, public opinion, and media in shaping foreign-policy preferences.

This study therefore investigates the relationship between human rights and foreign policy and examines the central question of how states can balance national interests with international human-rights norms.

2. Problem Statement

The principal problem examined in this research is the persistent gap between the international recognition of human rights and their consistent incorporation into foreign-policy decisions.

International human-rights law establishes obligations for states. Through international treaties, states undertake duties to respect, protect, and fulfil human rights. However, the existence of international obligations does not automatically guarantee consistent implementation. Foreign-policy decisions remain influenced by strategic calculations, domestic political interests, economic considerations, security concerns, and relationships among powerful states.

This creates a fundamental contradiction within contemporary international relations. On the one hand, states publicly affirm the universality of human rights. On the other hand, governments may respond differently to similar human-rights situations depending on their strategic relationships with the states concerned.

The problem is therefore not simply whether human rights matter in foreign policy. Rather, it is **under what conditions human rights become influential in foreign-policy decision-making and when they are subordinated to national interests**.

Understanding this tension is important because selective application of human-rights principles can weaken the credibility of international institutions and undermine confidence in the rules-based international order.

3. Research Questions

Main Research Question

How do states balance national interests with international human-rights norms in contemporary foreign-policy decision-making?

Sub-Questions

1. What role do human-rights norms play in contemporary foreign policy?
2. How do national security and economic interests influence human-rights-based foreign-policy decisions?
3. Why do states sometimes apply human-rights principles selectively?
4. What role do international organizations play in promoting human rights through foreign policy?
5. How effective are diplomatic pressure, sanctions, foreign assistance, and international cooperation in improving human-rights practices?
6. How can states reconcile legitimate national interests with international human-rights obligations?

4. Research Objectives

The general objective of this research is to examine the relationship between human rights and foreign policy and analyze the tension between national interests and international human-rights norms.

The specific objectives are:

1. To examine the development of human rights as an issue in international relations.

2. To analyze the influence of human-rights norms on foreign-policy decision-making.
3. To investigate the conflict between national interests and international human-rights obligations.
4. To examine the role of international organizations in protecting and promoting human rights.
5. To assess the effectiveness of foreign-policy instruments used to promote human rights.
6. To identify mechanisms through which states can achieve a more consistent balance between national interests and human-rights commitments.

5. Significance of the Study

This research is significant for both academic and policy-oriented reasons.

From an academic perspective, the study contributes to the International Relations literature by examining the relationship between material interests and normative commitments. The subject connects several major areas of IR scholarship, including realism, liberalism, constructivism, international law, global governance, and foreign-policy analysis.

From a policy perspective, the research highlights the challenges faced by governments when human-rights objectives conflict with security, economic, or geopolitical priorities. Understanding these challenges can contribute to more consistent and credible foreign-policy strategies.

The study is also relevant to international organizations, diplomatic institutions, civil-society organizations, and policymakers seeking to strengthen the international human-rights system.

6. Literature Review

6.1 Human Rights and the International System

The contemporary international human-rights regime developed principally after the Second World War. The UDHR established a universal statement of fundamental rights and freedoms and became the foundation for the subsequent development of international human-rights law.

The international framework subsequently expanded through legally binding treaties, including the International Covenant on Civil and Political Rights and the International Covenant on Economic, Social and Cultural Rights. Together with the UDHR, these instruments form what is commonly known as the International Bill of Human Rights.

This development changed traditional conceptions of sovereignty. Although states remain the principal actors in the international system, their treatment of individuals increasingly became a legitimate concern of international institutions and other states.

6.2 Human Rights and Foreign-Policy Analysis

Foreign-policy scholarship has increasingly examined human rights as an element of state behavior. The literature considers whether states should make human-rights promotion an explicit foreign-policy objective and whether governments actually implement policies consistent with their human-rights rhetoric.

Murdie (2024), for example, reviews the relationship between human rights and foreign-policy analysis and identifies foreign-policy instruments such as sanctions, military intervention, and foreign assistance as mechanisms that can influence human-rights outcomes. The study also emphasizes the influence of NGOs, civil society, media, and public opinion.

This literature demonstrates that human-rights foreign policy is not produced exclusively by government leaders. Domestic institutions and transnational actors can influence how human-rights issues are interpreted and incorporated into foreign policy.

6.3 Realism and National Interest

Realist theories traditionally place the state and national interest at the center of international relations. From this perspective, governments operate within an international system characterized by competition, uncertainty, and the absence of a centralized global authority.

National security and state survival therefore receive priority. Human rights may be supported when their promotion is compatible with strategic interests, but governments may be reluctant to sacrifice security or important alliances solely to protect rights abroad.

This perspective helps explain why states may maintain relationships with governments accused of serious human-rights violations when those relationships serve important security, economic, or geopolitical purposes.

6.4 Liberalism and International Institutions

Liberal approaches provide a different explanation. Liberal institutionalism emphasizes the importance of international institutions, international law, cooperation, and interdependence.
From this perspective, international institutions can establish rules that constrain state behavior and provide mechanisms through which human-rights concerns can be raised. The UN system, international courts, treaty bodies, and regional organizations all contribute to this process.
The UN emphasizes that international human-rights law establishes obligations requiring states to respect, protect, and fulfil human rights.

6.5 Constructivism and International Norms

Constructivist approaches emphasize the role of norms, identities, ideas, and social expectations in international politics. From this perspective, state interests are not entirely fixed; they can be influenced by changing international norms.
The growing international acceptance of human rights has therefore altered what governments consider legitimate behavior. A state may promote human rights not only because doing so produces material benefits but also because international norms influence its identity and understanding of appropriate conduct.
This provides an important explanation for why human rights have become part of diplomatic language and international political discourse even when their implementation remains inconsistent.

7. Theoretical Framework

This study uses a **combined theoretical framework based primarily on realism, liberal institutionalism, and constructivism**.

Realism

Realism explains the importance of national interest, security, power, sovereignty, and strategic calculations. It helps explain situations in which governments prioritize strategic partnerships over human-rights concerns.

Liberal Institutionalism

Liberal institutionalism explains how international organizations, treaties, international law, and multilateral cooperation can influence state behavior.

Constructivism

Constructivism explains how international norms and ideas influence state preferences and perceptions of legitimate behavior.
Combining these approaches provides a more comprehensive analytical framework. No single theory fully explains the complex relationship between human rights and foreign policy. Material interests matter, but so do institutions and norms.

8. Methodology

8.1 Research Approach

This study employs a **qualitative research approach**. The research focuses on interpreting existing academic literature, international legal instruments, institutional reports, and foreign-policy scholarship.

8.2 Research Design

A qualitative **descriptive and analytical research design** is employed. The study does not attempt to measure human-rights performance statistically. Instead, it analyzes the political and institutional mechanisms through which human-rights concerns interact with foreign-policy objectives.

8.3 Data Sources

The study relies on secondary sources, including:

- Peer-reviewed academic literature;
- Books and academic publications on International Relations;
- United Nations documents;
- International human-rights treaties;
- Reports from international organizations;
- Foreign-policy analyses;
- Relevant institutional and policy documents.

The UDHR and other UN materials are particularly important because they provide the normative and legal foundation for the international human-rights framework.

8.4 Data Analysis

The collected materials are analyzed thematically. Four principal themes guide the analysis:

1. Human rights as an international norm;
2. National interest and state sovereignty;
3. Foreign-policy instruments for human-rights promotion;
4. Geopolitical selectivity and implementation challenges.

9. Human Rights as an International Norm

Human rights have developed from a primarily domestic concern into an important component of international political discourse. The UDHR's recognition of universal rights established a normative foundation for subsequent international cooperation.

The importance of the UDHR extends beyond its original declaration. It inspired the development of numerous international human-rights treaties and continues to influence international and domestic legal systems.

The internationalization of human rights means that governments are increasingly expected to justify their policies not only in terms of domestic law but also through international standards.

However, norms do not automatically determine state behavior. Governments interpret and prioritize norms within specific political contexts. As a result, the existence of a widely accepted norm does not eliminate conflicts between human rights and national interests.

10. National Interests and Human Rights

National interest is one of the most important concepts in foreign-policy analysis. It generally encompasses objectives such as national security, territorial integrity, economic prosperity, political stability, and international influence.

The difficulty arises when these objectives conflict with human-rights considerations.

For example, a government may face a choice between criticizing a strategically important partner for human-rights violations and maintaining a security or economic relationship. A government may also hesitate to impose sanctions because sanctions can damage bilateral economic relations or create unintended humanitarian consequences.

This demonstrates that the relationship between human rights and national interest is not always a simple opposition. In some circumstances, human rights can support national interests. Stable institutions, rule of law, social development, and respect for human dignity can contribute to long-term political stability and international cooperation.

Therefore, the central challenge is not necessarily choosing between human rights and national interest but determining whether foreign policy can integrate both objectives.

11. Foreign-Policy Instruments for Promoting Human Rights

States and international organizations employ several instruments to promote human rights.

11.1 Diplomatic Pressure

Diplomatic engagement is one of the most common mechanisms. Governments may raise human-rights concerns through bilateral negotiations, international forums, diplomatic statements, or formal resolutions.

Diplomacy has the advantage of allowing states to communicate concerns without immediately damaging bilateral relations.

11.2 Economic Sanctions

Economic sanctions are frequently used to pressure governments accused of serious violations.

However, sanctions are controversial. Targeted sanctions can impose costs on responsible officials while minimizing broader humanitarian consequences, whereas comprehensive sanctions can have wider economic effects.

Therefore, the effectiveness and legitimacy of sanctions depend heavily on their design and implementation.

11.3 Foreign Assistance

Development assistance can be used to support democratic institutions, education, judicial reform, civil society, and human-rights protection.

Foreign aid can therefore serve both humanitarian and strategic purposes. However, attaching political conditions to aid may create tensions between donor objectives and recipient sovereignty.

11.4 International Institutions

International organizations provide mechanisms for monitoring, reporting, and addressing human-rights violations. The UN human-rights system includes treaty bodies and institutional mechanisms designed to support implementation and accountability.

These mechanisms contribute to international accountability, although their effectiveness depends on political cooperation and institutional capacity.

12. The Role of International Organizations

International organizations play a central role in establishing and maintaining international human-rights norms.

The United Nations is particularly significant. Human rights are incorporated into the UN Charter and have become one of the organization's major areas of activity.

The UN system contributes through:

- Human-rights monitoring;
- International reporting;
- Treaty mechanisms;
- Human-rights investigations;
- Technical assistance;
- Diplomatic engagement;
- International advocacy.

International organizations also provide forums in which states can be held accountable through international scrutiny.

Nevertheless, international organizations face limitations. Their ability to respond to violations may be affected by political disagreements among member states, institutional constraints, sovereignty concerns, and the unequal distribution of power.

13. Geopolitical Selectivity and Double Standards

One of the most serious challenges to human-rights foreign policy is **selective implementation**.

States may condemn violations committed by geopolitical competitors while responding more cautiously to violations committed by allies or strategic partners. Such behavior can create perceptions of double standards.

Selective application can damage the legitimacy of international human-rights institutions because governments and populations may question whether human rights are genuinely universal or are being used instrumentally.

From a realist perspective, such selectivity can be explained through strategic interests. From a constructivist perspective, however, inconsistent behavior can weaken the legitimacy of international norms.

A more credible human-rights foreign policy therefore requires greater consistency in responding to violations regardless of the political identity or strategic importance of the state involved.

14. Sovereignty and International Human Rights

State sovereignty remains a fundamental principle of international relations. Governments generally retain authority over domestic affairs, while the international system is based on the formal equality and independence of states.

At the same time, international human-rights law places obligations on states concerning the treatment of individuals within their jurisdiction. The development of international human-rights law has therefore created a complex relationship between sovereignty and international accountability.

The UN explains that states that ratify human-rights treaties assume international obligations to respect, protect, and fulfil human rights.

The challenge is to distinguish legitimate respect for sovereignty from the use of sovereignty as a justification for avoiding international obligations.

15. Human Rights, Security, and Foreign Policy

Security considerations frequently influence human-rights policy.

Governments may argue that restrictions on certain rights are necessary to combat terrorism, prevent armed conflict, or maintain national security. At the same time, excessive restrictions can undermine fundamental rights and create new sources of instability.
This creates a security dilemma in which policies intended to increase short-term security may produce long-term political and social problems.
A comprehensive foreign-policy approach should therefore recognize that human security and national security are interconnected. Respect for human dignity, rule of law, and accountable institutions can contribute to long-term stability.
The UN has similarly emphasized the relationship between human rights, rule of law, peace, security, and development.

16. The Role of Non-State Actors

Contemporary human-rights foreign policy is not shaped exclusively by states.
Non-governmental organizations, international advocacy groups, journalists, academic institutions, and civil-society organizations can influence international perceptions of human-rights violations.
These actors can:

- Document human-rights abuses;
- Disseminate information;
- Mobilize international public opinion;
- Pressure governments;
- Advocate for sanctions;
- Support victims;
- Influence international institutions.

Recent scholarship specifically identifies NGOs, civil society, media, and public opinion as relevant actors in foreign-policy decisions concerning human rights.
The growth of digital communication has further increased the speed at which information about human-rights violations can reach international audiences.

17. Discussion

The analysis demonstrates that human rights and national interests should not necessarily be understood as completely incompatible objectives.
The realist perspective correctly highlights the importance of security, sovereignty, and strategic interests. States cannot ignore these considerations when making foreign-policy decisions. However, a purely realist explanation cannot fully account for the growing influence of international human-rights norms.
Liberal institutionalism demonstrates how international institutions and legal commitments can constrain and influence state behavior. International organizations provide mechanisms for cooperation and accountability that would not exist through bilateral relations alone.
Constructivism adds another important dimension by demonstrating that state interests themselves can evolve as international norms change. Human rights have become sufficiently institutionalized that governments increasingly need to address them in their international relations.
The central finding of this study is therefore that **foreign policy operates within a multidimensional environment in which material interests, institutional constraints, and international norms interact**.
Human-rights promotion becomes more likely when it is compatible with strategic interests, supported by international institutions, reinforced by domestic constituencies, and embedded within widely accepted international norms.
Conversely, human-rights concerns are more likely to be marginalized when they threaten significant security partnerships, economic interests, or geopolitical objectives.
This explains why international human-rights policy frequently demonstrates inconsistency.

18. Recommendations

Based on the analysis, the study proposes the following recommendations:
1. Promote consistency

States should apply human-rights standards consistently rather than selectively according to political alliances.

2. Strengthen multilateral institutions

International institutions should be provided with stronger mechanisms for monitoring, reporting, and accountability.

3. Improve targeted sanctions

Where sanctions are necessary, governments should prioritize targeted measures that minimize unintended humanitarian consequences.

4. Integrate human rights into diplomacy

Human rights should be incorporated into diplomatic engagement rather than treated exclusively as a mechanism for punishment.

5. Strengthen civil society

International organizations and states should support legitimate civil-society actors that document and promote human rights.

6. Improve policy coordination

Foreign-policy, security, development, and human-rights policies should be coordinated rather than developed independently.

7. Avoid politicization

Human-rights mechanisms should be protected from excessive geopolitical manipulation because perceived double standards undermine international legitimacy.

19. Conclusion

Human rights have become an established component of contemporary international relations and foreign policy. Since the adoption of the Universal Declaration of Human Rights in 1948, the international community has developed an extensive body of human-rights norms and legal instruments. Nevertheless, the incorporation of human rights into foreign policy remains complicated. States must simultaneously pursue national security, economic prosperity, political stability, sovereignty, and strategic interests while responding to international expectations concerning human rights.

The analysis demonstrates that neither national-interest explanations nor normative approaches alone are sufficient to explain state behavior. Realist considerations remain important because governments continue to prioritize security and strategic interests. Liberal institutions influence state behavior through treaties, organizations, and international mechanisms. Constructivist processes demonstrate that international norms and ideas can reshape state preferences and perceptions of legitimate behavior.

The central challenge is therefore not to eliminate national interest from foreign policy, which is unrealistic, but to develop foreign-policy frameworks in which national interests and international human-rights obligations can be pursued in a more coherent manner.

A credible international human-rights policy requires consistency, accountability, effective diplomacy, stronger international institutions, and respect for international law. States should recognize that human rights are not merely an external policy instrument but an essential component of a stable international order.

Ultimately, the long-term credibility of the international human-rights system depends on reducing the gap between normative commitments and actual foreign-policy behavior. A foreign policy that consistently integrates human dignity, international law, security, and legitimate national interests can contribute not only to the protection of individuals but also to international peace, stability, and cooperation.

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POST-CONFLICT RESETTLEMENT PROGRAMME AND SOCIO-ECONOMIC DEVELOPMENT IN BAMA LOCAL GOVERNMENT AREA, BORNO STATE, NIGERIA

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Abstract
This study examines the relationship between resettlement programmes and socio-economic development in Bama Local Government Area (LGA), Borno State, Nigeria, focusing on the reintegration of internally displaced persons (IDPs), promotion of social stability, and facilitation of economic recovery. Guided by Post-Conflict Recovery Theory, the study employed a mixed-methods design comprising a structured Likert-scale questionnaire administered to 412 validated respondents and key informant interviews (KIIs) with 15 community leaders in Bama LGA. Quantitative data were analysed using descriptive statistics and multiple linear regression, while qualitative data were analysed thematically. Descriptive findings indicate a moderately positive perception of resettlement initiatives, particularly regarding reintegration, social stability, and livelihood recovery. However, inferential analysis found no statistically significant relationship between resettlement programme variables and socio-economic development ($F = 0.690$, $p = 0.631$), leading to acceptance of the null hypothesis that resettlement programmes do not significantly predict reintegration, social stability, and economic recovery outcomes in Bama LGA. Thematic analysis corroborates this divergence, revealing that while resettlement has facilitated physical return through shelter and livelihood support, full social and psychological reintegration remains constrained by land disputes, funding shortfalls, weak institutional coordination, and persistent trauma. This gap between perceived progress and statistically measurable outcomes underscores the complexity of post-conflict recovery, in which visible physical resettlement does not automatically translate into holistic socio-economic transformation. The study concludes that resettlement programmes in Bama LGA have laid an important foundation for recovery but require sustained investment, equitable resource distribution, and stronger stakeholder collaboration to achieve measurable socio-economic transformation. It recommends that government agencies and humanitarian actors prioritise land tenure resolution, adequate funding, and coordinated institutional support to strengthen the sustainability of resettlement outcomes.
Keywords: Resettlement; Reintegration; Internally Displaced Persons; Socio-Economic Development; Bama, Borno State

SHARED WATERS, DIVERGENT RULES: SRI LANKA, THE UAE, AND THE GOVERNANCE OF PRIVATE MARITIME SECURITY INFRASTRUCTURE IN THE INDIAN OCEAN

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Abstract
The Indian Ocean has become a major theater of maritime trade, strategic rivalry and non-traditional security issues. Alongside the growth of state-led maritime security initiatives, the region has seen the increasing involvement of private maritime security companies (PMSCs), including companies engaged in vessel protection, the provision of security staff, arms storage and floating armory facilities. While private maritime security has played a role in combating piracy and securing commercial shipping, its proliferation has also raised difficult questions of jurisdiction, accountability, arms control and the right balance between state power and private security provision. This paper comparatively examines the governance of private maritime security infrastructure in Sri Lanka and the United Arab Emirates (UAE). The two cases are particularly significant because both occupy strategically important positions within Indian Ocean maritime networks but have developed different institutional and regulatory approaches towards private maritime security. Sri Lanka provides an important case of the regulatory challenges associated with floating armouries, private security companies, and the management of maritime security activities within a sovereign territorial framework. The UAE, in contrast, represents a major maritime, logistics, and commercial security hub where private maritime security activities have developed alongside extensive state regulatory and port-security mechanisms. Using a qualitative comparative approach based on policy documents, national regulations, international maritime-security frameworks, and secondary literature, the paper analyses differences in licensing, arms management, institutional oversight, accountability, and state–private security relations. It argues that the contrasting experiences of Sri Lanka and the UAE demonstrate a broader governance dilemma in the Indian Ocean: maritime security infrastructure may operate across national jurisdictions, while regulatory authority remains primarily national. The paper therefore explores the need for greater regional coordination and harmonisation of regulatory standards to ensure transparency, accountability, and responsible private-sector participation in Indian Ocean maritime security governance.
Keywords: Indian Ocean, Private Maritime Security Companies, Sri Lanka; United Arab Emirates, Maritime Governance

Introduction
Private maritime security has evolved from an emergency response to piracy into a durable element of ocean governance, as shipowners combine armed protection, insurance, routing, and information exchange rather than relying solely on naval patrols (Stockbruegger, 2021). Flag states retain formal authority over vessels, but coastal states, port states, international organisations, insurers, and industry

bodies exercise overlapping forms of control (Gould, 2020; Yu et al., 2017), producing what this paper terms maritime security infrastructure: the material, legal, commercial, and organisational arrangements through which threats are identified and addressed. This infrastructure increasingly links vessel protection to port security, cybersecurity, and critical-infrastructure protection (Bueger & Edmunds, 2017; Liebetrau & Bueger, 2024).

This paper asks how private maritime security infrastructure is governed when sovereign jurisdiction, commercial risk management, and regional strategy overlap, comparing Sri Lanka and the UAE as two Indian Ocean settings with unevenly documented experiences. Its central argument is that private maritime security does not produce a uniform transfer of sovereign authority; outcomes instead depend on how states connect firms to licensing, port administration, naval coordination, and international standards. The UAE case illustrates state-led regional security governance and the strategic deployment of PMSCs, while Sri Lanka is treated more cautiously as a site where maritime security intersects coastal authority but where country-specific evidence remains limited (Ammar, 2020). The comparison is interpretive, drawing on legal scholarship, governance theory, industry analysis, and quantitative piracy research, rather than equivalent national datasets for both cases.

Literature Review

Sovereignty at sea remains a central legal principle under pressure from functional and commercial governance. Flag-state jurisdiction is the primary basis for regulating ships and crew, but weak flag-state control has pushed port and coastal states and international organisations to expand their own regulatory reach (Yu et al., 2017). Because a vessel may be owned, flagged, operated, and protected across different states, Gould (2020) describes Indian Ocean maritime security as an assemblage of flags of convenience, international bodies, and commercial actors in which private authority emerges through mutually reinforcing practices rather than a single delegation. The legal distinction between piracy on the high seas and armed robbery in territorial waters further complicates matters, since a guard's use of force can carry different legal meaning depending on location (Svanberg, 2020). Svanberg concludes that the combined framework of UNCLOS, SOLAS, customary self-defence, IMO guidance, and national law is adequate only insofar as national procedures translate general standards into licensing and use-of-force rules (Svanberg, 2020, 2021).

Public–private security assemblages describe how states, firms, international bodies, and industry associations jointly produce security practice, moving beyond a simple state-versus-market frame (Pranava Rasahugan & Khalil, 2021; Xiong et al., 2018). Stockbruegger (2021) shows that shipowners turn to PMSCs and piracy insurance because naval forces cannot provide continuous day-to-day protection, with the United States shaping the rules within which private protection operates; Magunna (2024) finds a parallel pattern in Southeast Asia, where growing regional capacity coincided with greater governance influence for insurers and shippers rather than the state simply displacing private actors. Different private actors relate to regulation differently: licensing controls a guard company directly, while insurers and shippers exert indirect influence through pricing and routing. Prem (2021) cautions that multi-stakeholder initiatives can nonetheless entrench PMSCs as legitimate actors while marginalising critics of privatisation, since resourced and expert actors shape what counts as a feasible regulatory solution.

On accountability, private personnel are not automatically equivalent to naval officers or police; their authority depends on flag, coastal or port law, contract, and circumstance. Svanberg (2021) finds the combined legal framework adequate only when implemented nationally, while Holikov and Okocha (2021) stress the blurred line between lawful protection and illegal weapons use. Cross-border misconduct is harder to address, since PMSC operations can fall outside the effective jurisdiction of host state, home state, or international law (Muayed Lalyoyevich, 2024), and corporate form can insulate decision-makers from liability (Galai, 2019; Nebolsina, 2021). Stiernstedt et al.'s (2019) three-pillars model – sectoral regulation, equitable access to security, and public-interest responsibility – offers a useful accountability lens, directing attention to seafarers and coastal populations, not only shipowners and contractors.

Methodology

The study combines doctrinal and interpretive analysis. The doctrinal component maps how UNCLOS, SOLAS chapter XI-2, the ISPS Code, customary self-defence, and national law interact and allocate jurisdiction (Organization, 2021; Svanberg, 2020). The interpretive component examines how states and

firms understand private protection within broader security governance, since maritime security is implemented through formal and informal sources; the absence of a single international convention is treated as a finding about regulatory structure rather than evidence that no rules apply. Evidence is read with attention to its limits: quantitative studies can show association between private protection and reduced piracy risk but cannot explain national licensing practice, while interpretive case studies illuminate policy rationale without establishing operational frequency. The UAE literature is policy-focused and does not evaluate legality, and the Sri Lanka material is insufficient for detailed national reconstruction (Ammar, 2020).

Comparative case analysis connects four levels: the firm (contracted function, use-of-force boundaries, certification), the state (licensing, jurisdiction, coordination with naval or coastal authorities), the port (access, inspection, embarkation), and the transnational (IMO instruments, industry guidance, insurance, multilateral initiatives). This governance-chain approach follows the literature's insistence that maritime security links land and sea, information, and capacity-building (Bueger & Edmunds, 2017), and allows comparison between the UAE's state-directed incorporation of PMSCs and Sri Lanka's more fragmented, less-documented commercial provision (Ammar, 2020).

Findings

The UAE case shows PMSCs connected to a state's regional security strategy rather than functioning only as commercial substitutes for naval power. The relevant study situates UAE policy within Regional Security Complex Theory, presenting PMSCs as instruments through which the UAE pursues regional influence while limiting its own exposure to a conflict-affected Middle East, without assessing the legal status or accountability of those activities (Ammar, 2020). This differs from Stockbruegger's (2021) commercially driven model: in the UAE, “private” describes organisational form rather than political direction, since state direction can align procurement, training, and diplomacy more readily than a dispersed shipowner market, even as accountability becomes dependent on domestic executive oversight rather than transparent transnational procedure (Muayed Lalyoyevich, 2024). The available UAE literature documents strategic policy, not specific maritime contracts or incidents, so conclusions about UAE maritime operations remain analytical rather than empirical.

The Sri Lanka case must be built more cautiously, since no comparable country-specific study of licensing, procurement, or contractor conduct exists. The defensible finding is that Sri Lanka functions as a coastal and port setting within a regional system where ships, providers, and standards cross jurisdictional boundaries, with coastal authority mattering most where private security intersects territorial waters and armed robbery rather than high-seas piracy (Svanberg, 2020; Yu et al., 2017). Mechanisms visible in the regional literature – captain–owner–insurer relationships (Tung, 2017) and ISPS Code administration (Organization, 2021) – create an institutional vocabulary without proving Sri Lankan implementation. The case illustrates a distinction between regulatory presence and regulatory observability: standards may exist formally while enforcement remains difficult to observe in the literature (Larsen, 2026), a gap that should be read as a call for direct legal and administrative research rather than evidence of weak governance.

Both cases share exposure to similar pressures. DeAngelo and Smith (2020), using IMO vessel-security data from 2007–2014, found that private security reduced piracy-related risk for protected vessels and generated spillover risk reductions for unsecured vessels, framing private protection as a contributor to international public safety rather than only private benefit. Yet shared exposure does not produce shared regulation: the UAE case makes private force legible as state strategy, while Sri Lanka remains legible mainly through distributed jurisdiction and international standards, showing that geographic proximity cannot substitute for institutional comparison. A state-directed arrangement concentrates authority in government decisions; a commercially organised arrangement distributes influence among owners, insurers, and flag states (Gould, 2020; Magunna, 2024).

Infrastructure and Standards

Private maritime security operates through an interlocking chain of sites rather than the guard team alone. The ship is where risk assessment, watchkeeping, and escalation decisions occur, with the purchase of protection driven by shipowners, charterers, and insurers (Stockbruegger, 2021; Tung, 2017). The port is a second site, since guards, weapons, and documentation cross a territorial threshold even though the ship itself remains under flag-state jurisdiction while underway; port- and coastal-state controls have expanded in response to deficient flag-state oversight (Yu et al., 2017; Organization,

2021). Insurance is a third, less visible site: premiums and conditions translate security decisions into commercial incentives, and as regional capacity grows, insurers and shippers increasingly shape anti-piracy order (Stockbruegger, 2021; Magunna, 2024). This circuit has no single point of control, and failure can arise from poor vetting, unclear command, weak port coordination, or absent reporting (Xiong et al., 2018; Tung, 2017).

The ISPS Code, implemented through SOLAS chapter XI-2, supplies a common transnational reference point, requiring legal, administrative, verification, and enforcement capacity from states (Organization, 2021). Private armed protection sits partly inside and partly alongside this architecture, supplemented by IMO guidance, ISO standards, the Montreux Document, and industry codes (Svanberg, 2020, 2021). Soft guidance can be revised quickly and coordinate actors without a shared regulator, including on cyber risk (Organization, 2021), but it depends on national incorporation and credible auditing; Anwar et al. (2021) show that importing land-based private-security rules into Malaysian maritime regulation without reconciling them with maritime law can itself produce inconsistency. The agenda has also expanded from protecting individual vessels toward critical maritime infrastructure – ports, subsea systems, and cyber-dependent operations – where counter-piracy and cybersecurity governance share lessons in information-sharing and coordinated action (Liebetrau & Bueger, 2024; Bueger et al., 2025), and where armed guards alone cannot secure port networks or resolve the underlying socioeconomic drivers of piracy (Bueger & Edmunds, 2017).

The Naval–PMSC Debate

PMSCs address a mismatch between continuous commercial shipping schedules and broad, public-mission naval patrols (Stockbruegger, 2021). DeAngelo and Smith (2020) provide the strongest quantitative support for effectiveness, showing both a direct risk reduction for protected vessels and an external effect in which protection on as few as 10% of attacked vessels lowered risk for unsecured vessels. Yet guards deter rather than enforce: they do not investigate, prosecute, or secure coastal communities, functions naval and coast-guard forces combine with rescue and jurisdiction (Korpela, 2025). Staritsyna (2019) notes navies are perceived as safer and more legitimate but costlier to maintain, making contractors more accessible to individual shipowners even as they underprovide the collective surveillance that DeAngelo and Smith's spillover finding implies. The literature therefore supports a hybrid arrangement – PMSCs for targeted onboard protection, naval assets for area security and enforcement – rather than a universal preference for either.

Delegating armed authority nonetheless carries risks: the boundary between self-defence and law enforcement varies by flag and jurisdiction and lacks a single directly applicable rule (Svanberg, 2020, 2021); command can be ambiguous between master, company security officer, and armed team, particularly with sensitive cargo (Tung, 2017); certification can normalise private force while marginalising critics of privatisation (Prem, 2021); and corporate personality can obscure accountability across borders (Galai, 2019; Muayed Lalyoyevich, 2024). These risks justify clear boundaries – licensing, training, and reporting for defensive functions, direct state responsibility for coercive enforcement – rather than a blanket prohibition on private provision.

Accountability and Evidence Gaps

Multi-stakeholder accountability is valuable because maritime knowledge is distributed, but participation does not equal influence: Prem (2021) identifies power exercised through rules, structural position, and discourse, meaning resourced actors can shape the regulatory agenda before formal decisions occur, even as their operational expertise genuinely improves technical standards. Structural position also determines whose risks become visible – shipowners can transfer risk through insurance, while affected coastal communities often lack comparable institutional access (Stiernstedt et al., 2019) – and the fragmented character of maritime law across UNCLOS, SOLAS, national rules, and contracts can let each actor define responsibility narrowly (Bueger et al., 2025). Accountability therefore requires institutional interfaces – verified licensing, pre-deployment rules, incident reporting, and clear investigative authority – not merely more participants.

The literature also leaves Sri Lanka significantly under-researched as a regulatory jurisdiction: existing work addresses the Western Indian Ocean generally (Gould, 2020) or other cases such as the UAE, Southeast Asia, and Malaysia (Anwar et al., 2021; Magunna, 2024; Ammar, 2020), without documenting Sri Lankan licensing, firearms control, or investigative authority. This is both an empirical and doctrinal gap: the IMO's implementation framework specifies general requirements (Organization,

2021) but cannot substitute for country-specific research combining legislation, port procedure, and interviews. More broadly, fragmented regulation across flag, port, and coastal authority, SOLAS/ISPS, national firearms law, and industry guidance can displace or hide responsibility (Svanberg, 2020; Yu et al., 2017), and infrastructure-focused research is needed to make visible the contractual and logistical processes that formal rules alone do not capture (Larsen, 2026).

Conclusion

The UAE and Sri Lanka should not be assessed through a single model of privatisation. UAE policy illustrates state-directed use of PMSCs within regional security governance (Ammar, 2020), while Sri Lanka requires further study precisely because existing evidence cannot establish whether authority there is concentrated, commercially distributed, or divided among agencies. Indian Ocean cooperation should accordingly support information exchange and compatible standards – covering registration, vetting, weapons control, incident reporting, and remedy – while preserving explicit national responsibility for authorisation and oversight, since soft law and industry standards alone cannot resolve accountability gaps or unequal participation (Prem, 2021; Stiernstedt et al., 2019; Svanberg, 2020).

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PROMISES UNKEPT: JIMMY CARTER, THE ANTI-APARTHEID MOVEMENT, AND THE GAP BETWEEN HUMAN RIGHTS RHETORIC AND ACTION

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Abstract
When Jimmy Carter entered the White House in 1977, he promised a foreign policy rooted in human rights, offering profound hope to those fighting against South Africa's brutal apartheid regime. This paper explores the tragic disconnect between the Carter administration's soaring moral rhetoric and its cautious, often disappointing reality. Drawing on qualitative historical analysis—including executive speeches, congressional hearing transcripts, and movement archives—this study examines how Carter's initial condemnation of Pretoria ultimately buckled under the weight of American corporate interests. The findings reveal a frustrating paradox: while Carter and Ambassador Andrew Young successfully changed the conversation around apartheid, they refused to disrupt the roughly $2 billion in U.S. corporate investments propping up the racist regime. Even following the murder of activist Steve Biko, Carter protected corporate America by vetoing international investment bans and relying on voluntary, toothless corporate reforms. However, this executive betrayal inadvertently sparked a political rebellion. Frustrated by Carter's timidity, the Congressional Black Caucus and allied lawmakers stepped into the void, transforming anti-apartheid activism from street protests into formal legislative battles. Ultimately, Carter's presidency was defined by a heartbreaking failure to match his words with action, yet his moral framing unintentionally provided Congress with the exact tools needed to lay the groundwork for the real sanctions that would come later.
Keywords: Jimmy Carter, Apartheid, Human Rights, Congressional Black Caucus, U.S. Foreign Policy

FEMALE BEAUTY AND SPRITUALITY IN CONTEMPORARY SOCIETY: A PHILOSOPHICAL ANALYSIS OF THEIR SIGNIFICANCE FOR FAMILY LIFE

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Abstract

The contemporary understand of female beauty has increasingly been shaped by physical appearance, consumer culture, media representation, social media and fashion often at the expense of its spiritual, relational, moral and cultural dimensions. The problem addressed by this study is that the reduction of female beauty to bodily appearance and commercial attractiveness may encourage objectification, unrealistic beauty standards, and unhealthy competition thereby wreathing some of the ethical and relational foundations upon which stable family life depends. The study aims to philosophically examine the relationship between female beauty and spirituality in contemporary society and to determine how their proper understanding may contribute to development and flourishing of family life. The study adopts critical analysis methodology because it critically analyze those concepts why the theoretical framework is base on value ethics, care ethics and African communitarian philosophy. However, the study also maintains that female beauty should not be treated as a woman's primary measure of worth or as an instrument for enforcing restrictive gender expectation. The study is justified by a need for a more holistic conception of beauty capable of responding to the contemporary transformations in family relationships and social values. The study concludes that the meaningful integration of aesthetic and spiritual value and contribute to heal their interpersonal relationship and flourishing of family life in contemporary society.

Keywords: Female beauty, spirituality, aesthetics, ethic, family life and human dignity.

ADVERTISING IN TRADITIONAL AND SOCIAL MEDIA: AUDIENCE PERCEPTIONS OF INFLUENCE, CREDIBILITY, AND SOCIAL RESPONSIBILITY IN ALBANIA

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Abstract
The transformation of the media environment and the development of digital technologies have changed the ways in which advertising is conceptualized, produced, and distributed, as well as the relationship between brands and consumers. From a predominantly one-way communication model, advertising communication has evolved into a more dynamic and interactive process in which audiences participate in the creation, distribution, and interpretation of content.
This study analyzes the perceptions of Albanian audiences regarding advertising in traditional and social media, focusing on the influence of advertising on consumer decision-making, the credibility of advertising messages, and perceptions of social responsibility in advertising communication. The study also examines the influence of social media influencers and the ways in which Albanian audiences evaluate advertising content and adherence to ethical principles and social responsibility.
The study adopts a mixed-methods approach, combining quantitative and qualitative research components. The quantitative component is based on data collected through a questionnaire administered to 318 respondents in Albania, while the qualitative component complements the interpretation of consumer perceptions of advertising communication.
The results indicate a high level of exposure to advertising, with 81.1% of respondents reporting that they encounter advertisements. Instagram emerges as the dominant channel of exposure, at 65.4%, while television remains an important channel, at 34.0%. However, high exposure does not necessarily correspond to high levels of trust, as 58.2% of respondents report that they do not trust the advertisements they encounter. In the comparison between channels, television advertising is perceived as more credible by 58.5% of respondents, while social media advertising is perceived as more credible by 47.2%.
Differences are also evident in perceptions of social responsibility. While 81.1% of respondents consider social responsibility important for consumers, 48.1% perceive television advertising as demonstrating social responsibility, compared with 30.8% for social media advertising and 22.3% for influencer advertising. The findings reveal differences between traditional and digital media environments in the ways Albanian audiences perceive the credibility and social responsibility of advertising communication.
Keywords: advertising; traditional media; social media; influencers; credibility; social responsibility; consumers; Albania.

1. Introduction
Advertising constitutes a complex communication phenomenon whose development has progressed alongside technological, economic, social, and cultural transformations. Beyond its promotional function, advertising interacts with audience perceptions, attitudes, and behavior, making it an important object of study within the field of communication.
Classical marketing definitions describe advertising as a paid and non-personal form of communication (Kotler & Armstrong, 2000), as persuasive communication mediated through mass media (Wells, Burnett, & Moriarty, 1998), or as a paid effort to persuade an audience through media (O'Guinn, Allen, & Semenik, 2000). Despite differences in formulation, these definitions share several common elements: the existence of an identifiable sponsor, the use of media as a communication channel, and the intention to influence audience attitudes or behavior.

With the development of digital technologies and the transformation of the media ecosystem, the concept of advertising has expanded beyond traditional approaches. Richards and Curran (2002) define advertising as a paid, mediated form of communication from an identifiable source, designed to influence the actions or attitudes of the receiver. Dahlén and Rosengren (2016) further extend the discussion of how advertising should be defined under conditions of a transforming media environment. The evolution of these definitions reflects the transformation of advertising practice itself. Nevertheless, several elements remain consistent: the existence of an identifiable source, mediation through media, the persuasive purpose of communication, and orientation toward a particular audience. In this sense, advertising remains a dynamic construct whose definition should reflect technological, media, and social transformations (Vangelov, 2023).

The transformation of media has directly influenced the development of advertising communication. In traditional media, advertisements were predominantly transmitted in a linear manner, and communication between brands and consumers was largely one-way. In digital environments, advertisements are intertwined with user activity, creating new forms of interaction and engagement.

The development of digital media does not imply the disappearance of traditional media. Rather, both forms coexist within the contemporary communication environment, offering different characteristics and opportunities for advertisers and audiences.

The distinction between advertising in traditional media and advertising in digital media constitutes the basis of this study for analyzing Albanian consumers' perceptions of the credibility, influence, and social responsibility of advertising communication.

At the same time, the shift of advertising toward digital environments has increased the importance of issues related to credibility, ethics, and social responsibility. On social platforms, advertising communication takes place in an environment where commercial content is intertwined with user activity and with new forms of communication mediated by influencers.

1.1 Purpose of the Study

The purpose of this study is to analyze Albanian audiences' perceptions of advertising in traditional and social media, focusing on the influence of advertising on consumer decision-making, the credibility of advertising messages, and perceptions of social responsibility in advertising communication.

The study aims to identify differences between advertising in traditional media and advertising in social media by examining how Albanian audiences evaluate advertising content, the influence of influencers, the credibility of information, and adherence to ethical principles and social responsibility.

1.2 Research Questions

1. What is the level of exposure of Albanian audiences to advertising in traditional and social media, and which platforms dominate advertising communication?
2. To what extent do advertisements and influencer-mediated communication affect the perceptions, preferences, and decision-making of Albanian consumers, particularly in relation to online purchases?
3. How do Albanian audiences perceive the credibility of advertising in traditional media compared with advertising in social media?
4. How do Albanian audiences evaluate the social responsibility of advertising in traditional and social media, particularly advertising carried out by influencers?
5. Do the perceptions of Albanian audiences support the proposition that advertising in traditional media demonstrates a higher level of social responsibility toward consumers than advertising in social media?

1.3 Research Hypotheses

H1. Advertising in traditional and social media influences the perceptions, credibility assessments, and decision-making of Albanian consumers through its informative and persuasive functions.

H2. Albanian audiences perceive advertising in traditional media as reflecting a higher level of social responsibility toward consumers than advertising in social media.

2. Literature Review and Theoretical Framework

Contemporary advertising represents a complex phenomenon that combines media communication, consumer psychology, marketing, and technological developments. Therefore, the analysis of its influence on consumer perceptions and behavior cannot rely on a single theoretical perspective.

The study develops its theoretical framework around three complementary theories: **Uses and Gratifications Theory, Social Comparison Theory, and Cultivation Theory**.

2.1 Uses and Gratifications Theory

Uses and Gratifications Theory is particularly associated with the contributions of Elihu Katz, Jay G. Blumler, and Michael Gurevitch and represents an important shift in the conceptualization of audiences. Rather than focusing exclusively on the influence of media on individuals, the theory directs attention toward the ways people select and use media to satisfy specific needs and objectives (Katz et al., 1974).

At the core of the theory is the idea that individuals select media and content that best serve their interests, expectations, and needs. These needs may relate to obtaining information, entertainment, emotional experience, the construction of personal identity, social interaction, or temporary escape from everyday life (Littlejohn et al., 2017).

According to this approach, media influence is not an automatic consequence of exposure but rather the result of the relationship between content, motivations for media use, individual characteristics, and the social context (McQuail, 2010).

Rubin (1981) made an important contribution to the empirical development of the theory by identifying motivations such as information seeking, entertainment, relaxation, passing time, social interaction, and emotional experience.

In this study, Uses and Gratifications Theory is applied to understand how Albanian consumers select and use traditional media and social platforms, as well as to interpret differences in exposure to advertising and the evaluation of advertising messages.

2.2 Social Comparison Theory

Social Comparison Theory, formulated by Leon Festinger (1954), explains how individuals evaluate their abilities, opinions, and social position in relation to others. In the absence of objective standards, individuals may use other people as points of reference, making social comparison an important mechanism in the construction of self-perception and self-evaluation (Festinger, 1954).

Social media platforms have created an environment particularly conducive to social comparison. Users are continuously exposed to images, videos, and personal narratives that may present selected and idealized versions of life, success, physical appearance, and consumption.

Vogel et al. (2014) found that frequent social media use is associated with higher levels of social comparison and lower self-esteem.

In advertising communication, Social Comparison Theory helps explain how consumers evaluate themselves in relation to the models represented in advertisements, public figures, and influencers. Advertisements do not merely promote the functional characteristics of a product; they also construct images of success, beauty, status, and desirable lifestyles.

In this study, the theory is used to explain the psychological mechanisms through which advertisements and influencer content may be associated with the perceptions, preferences, and decision-making of Albanian consumers.

2.3 Cultivation Theory

Cultivation Theory, developed by George Gerbner and his colleagues, focuses on the long-term effects of mass communication. Unlike approaches that focus on the immediate effects of media messages, the theory argues that media influence develops gradually and cumulatively.

Continuous exposure to media content does not necessarily change behavior following a single message, but over time it contributes to the formation of perceptions of reality (Gerbner & Gross, 1976).

From this perspective, television is conceptualized not merely as a source of information or entertainment but as a cultural institution that continuously transmits values, norms, stereotypes, and behavioral models (Gerbner et al., 1986).

For the present study, Cultivation Theory is used to interpret how continuous exposure to traditional and digital advertising may contribute to the gradual construction of perceptions concerning brands, products, consumption, credibility, and the social responsibility of advertising communication.

2.4 Integration of the Theoretical Framework

The complexity of contemporary advertising requires an integrated theoretical approach. Uses and Gratifications Theory serves to interpret media choice and use and the level of exposure to advertising. Social Comparison Theory explains psychological mechanisms related to identification with figures represented in the media and with influencers. Cultivation Theory examines the long-term effects of exposure and how the repetition of messages may contribute to the formation of perceptions.

The integration of the three theories creates an interpretative model that analyzes advertising at three interconnected levels: **media selection and use, psychological mechanisms of influence, and the long-term effects of media exposure**.

3. Research Methodology

3.1 Methodological Approach and Research Design

Research methodology determines how data are collected, analyzed, and interpreted by specifying the research approach, the instruments employed, sample selection, and methods of analysis. According to Kothari (2004), scientific research should be conducted systematically and according to a planned procedure.

The study adopts a **mixed-methods approach**, combining quantitative and qualitative research components. The selection of this approach derives from the need both to measure audience trends and attitudes and to interpret experiences and the ways in which social actors understand advertising communication.

Matthews and Ross (2010) argue that the selection of research methods depends on the type of data required to test hypotheses and answer research questions.

The research design combines quantitative research through a questionnaire, qualitative research through semi-structured interviews, direct observation of social media, and documentary analysis.

3.2 Data Collection Instruments

3.2.1 Questionnaire

The quantitative component employed a questionnaire to collect structured data concerning audience tendencies, attitudes, and perceptions related to advertising.

The instrument measured dimensions related to exposure to advertising, the main channels through which advertisements are encountered, trust and credibility, perceptions of advertising as information, influence, and culture, persuasive elements, and perceived social responsibility in television advertising, social media advertising, and influencer-mediated advertising.

The quantitative dataset consists of **318 valid responses** collected in Albania between **December 2024 and May 2025**.

3.2.2 Semi-Structured Interviews

To complement the quantitative data, **two semi-structured interviews** were conducted. The qualitative component includes interviews with **Greiss Petroviç**, in relation to Grace Models and AGA Clothing, and **Jozefina Luci Maliqaj**.

The interviews were used to clarify how concepts of influence and responsibility in advertising are understood in practice and to complement the interpretation of questionnaire results.

3.2.3 Observation and Documentary Analysis

The study also includes direct observation of social networks and online platforms, examining influencer profiles, visual and textual content, posts, stories, videos, comments, and audience interactions.

Documentary analysis includes studies, research reports, academic articles, and written materials published by influencers.

3.3 Study Sample

The quantitative sample consists of **318 respondents**. Of these, **274 are female (86.2%)**. The 18–24 age group includes **161 respondents (50.6%)**, while **59 respondents (18.6%)** are aged 45 years or older.

Regarding educational level, **245 respondents (77.0%)** have higher education, while **73 respondents (23.0%)** have completed secondary education.

The largest geographical concentrations are found in **Tirana, with 100 respondents (31.4%)**, **Fier with 46 (14.5%)**, **Burrel with 28 (8.8%)**, and **Durrës with 26 respondents (8.2%)**.

3.4 Data Analysis

The quantitative analysis employed frequencies, percentages, comparisons between groups, and the identification of key trends.

For the qualitative analysis, data from the interviews and online materials were examined through a thematic approach, identifying key themes, recurring responses, discursive patterns, and elements of meaning.

Data triangulation was used to integrate the quantitative and qualitative components in the interpretation of the findings.

3.5 Ethical Considerations and Methodological Limitations

The study takes into consideration voluntary participation, confidentiality, the anonymization of personal data, and the accurate representation of respondents' views without distorting their meanings.

Methodological limitations include the inability to fully control the authenticity of certain online interactions, the dynamic nature of social networks, where content may be changed or deleted, and the need for caution in the interpretation of qualitative material.

4. Results

4.1 Exposure to Advertising

Of the 318 respondents, **258, or 81.1%**, report that they encounter advertisements.

Regarding the channels of exposure, **Instagram** emerges as the dominant platform, selected by **208 respondents, or 65.4%**, while television was selected by **108 respondents, or 34.0%**.

The results therefore indicate a high level of exposure to advertising and a particularly strong presence of social media platforms.

4.2 Trust and Credibility

Only **133 respondents, or 41.8%**, report that they trust the advertisements they encounter, whereas **185 respondents, or 58.2%**, report that they do not trust them.

In the comparison between channels, **186 respondents, or 58.5%**, selected television advertising as more credible, while **150 respondents, or 47.2%**, selected social media advertising.

These results demonstrate that high exposure to advertising does not necessarily correspond to a high level of trust.

4.3 Perceptions of the Function of Advertising

213 respondents, or 67.0%, perceive advertising as **information**, **144 respondents, or 45.3%**, as **influence**, and **39 respondents, or 12.3%**, as **culture**.

The results indicate the predominance of the informational dimension while also demonstrating the considerable presence of advertising's influential function.

4.4 Influential Elements

Visual imagery emerges as the dominant element and was selected by **224 respondents, or 70.4%**.

Characters and brand ambassadors were selected by **109 respondents, or 34.3%**, while **music** was selected by **55 respondents, or 17.3%**.

These results highlight the importance of the visual and symbolic dimensions of advertising communication.

4.5 Social Responsibility

258 respondents, or 81.1%, state that social responsibility is important to consumers.

Regarding television advertising, **153 respondents, or 48.1%**, state that it demonstrates social responsibility. For social media advertising, this proportion falls to **30.8%, or 98 respondents**, while only **71 respondents, or 22.3%**, state that influencer advertising respects social responsibility.

Table 1. Main Empirical Indicators of the Study

Indicator	n	%
Report encountering advertisements	258	81.1
Encounter advertisements on Instagram	208	65.4
Encounter advertisements on television	108	34.0
Trust the advertisements they encounter	133	41.8
Do not trust the advertisements they encounter	185	58.2
Television advertising perceived as more credible	186	58.5
Social media advertising perceived as more credible	150	47.2
Advertising perceived as information	213	67.0
Advertising perceived as influence	144	45.3
Advertising perceived as culture	39	12.3
Visual imagery	224	70.4
Characters/brand ambassadors	109	34.3
Music	55	17.3
Social responsibility considered important	258	81.1
Television advertising perceived as socially responsible	153	48.1
Social media advertising perceived as socially responsible	98	30.8
Influencer advertising perceived as respecting social responsibility	71	22.3

Source: Primary survey conducted in Albania, 2024–2025.

5. Discussion

The results reveal a complex relationship between exposure to advertising, influence, credibility, and social responsibility.

5.1 Exposure and Credibility

The fact that 81.1% of respondents report encountering advertisements demonstrates the widespread presence of advertising communication. Instagram dominates exposure at 65.4%, while television continues to play an important role at 34.0%.

This finding can be interpreted in relation to Uses and Gratifications Theory, which conceptualizes the audience as active in the selection and use of media (Katz et al., 1974).

However, exposure does not automatically translate into trust. **58.2%** of respondents state that they do not trust the advertisements they encounter. In the comparison between channels, television advertising is perceived as more credible by 58.5% of respondents, compared with 47.2% for social media advertising.

The results therefore indicate that the visibility of advertising does not automatically guarantee its credibility.

5.2 Advertising as Information and Influence

The findings indicate that **67.0%** of respondents conceptualize advertising as information, while **45.3%** perceive it as influence.

The influential dimension becomes more evident when persuasive elements are examined. **Visual imagery, at 70.4%**, is the dominant factor, followed by characters or brand ambassadors at 34.3% and music at 17.3%.

In this context, Social Comparison Theory contributes to the interpretation of how models, public figures, and influencers may function as points of reference for audiences (Festinger, 1954; Vogel et al., 2014).

5.3 First Hypothesis

H1 proposes that advertising in traditional and social media influences the perceptions, credibility assessments, and decision-making of Albanian consumers through its informative and persuasive functions.

The empirical results **support the functional core of this hypothesis in a nuanced manner**.

Advertising is widely present in the audience's media experience and is perceived primarily as information, while a considerable proportion of the sample also identifies it as a form of influence. The dominance of visual imagery and the importance of characters and brand ambassadors further indicate that persuasion is not achieved exclusively through factual information but also through visual and symbolic elements.

The integrated theoretical framework contributes to the interpretation of this relationship: Uses and Gratifications Theory explains media selection and use; Social Comparison Theory explains the psychological mechanisms of comparison and identification; and Cultivation Theory explains the cumulative effects of continuous exposure (Katz et al., 1974; Festinger, 1954; Gerbner et al., 1986).

5.4 Social Responsibility

81.1% of respondents state that social responsibility is important to consumers. However, assessments of its presence in advertising communication are lower and differ according to the medium.

Television advertising is perceived as socially responsible by **48.1%**, compared with **30.8%** for social media advertising and **22.3%** for influencer advertising.

The results therefore reveal a difference between the importance audiences attribute to social responsibility and the extent to which they perceive it as being implemented in advertising practice.

5.5 Second Hypothesis

H2 proposes that Albanian audiences perceive advertising in traditional media as reflecting a higher level of social responsibility toward consumers than advertising in social media.

The empirical data clearly support this difference. Television advertising receives the highest assessment for social responsibility, at 48.1%, compared with 30.8% for social media advertising and 22.3% for influencer advertising.

Within the context of these findings, **the second hypothesis receives substantial empirical confirmation**.

However, the results should not be interpreted as evidence that social media are inherently ethically inferior. The dissertation conceptualizes digital ethics as an evolutionary phase in which responsibility is gradually shifting from institutions toward individuals.

6. Conclusions

This study analyzed Albanian audiences' perceptions of advertising in traditional and social media, focusing on exposure, influence, credibility, and social responsibility.

The results demonstrate that advertising is widely present in respondents' media experiences. **81.1%** report encountering advertisements, while Instagram emerges as the main channel of exposure at **65.4%**, compared with **34.0%** for television.

However, high levels of exposure are not automatically accompanied by trust. **58.2%** of respondents state that they do not trust the advertisements they encounter. In the comparison between channels, television maintains an advantage in terms of perceived credibility.

The findings also show that audiences perceive advertising primarily as information, while at the same time recognizing its influential function. The dominance of visual imagery as the most influential element demonstrates the importance of the visual and symbolic dimensions of advertising communication.

In this respect, the empirical results **provide nuanced support for H1**, according to which advertising in traditional and social media influences the perceptions, credibility assessments, and decision-making of Albanian consumers through its informative and persuasive functions.

One of the most significant findings concerns social responsibility. **81.1%** of respondents state that social responsibility is important to consumers. However, only **48.1%** perceive social responsibility in television advertising, **30.8%** in social media advertising, and **22.3%** in influencer advertising.

Consequently, **H2 receives substantial empirical confirmation**, as Albanian audiences perceive a higher level of social responsibility in traditional advertising than in social media advertising.

Overall, the study demonstrates that **exposure, influence, credibility, and social responsibility do not necessarily develop in parallel**. Social media may dominate advertising exposure, while traditional media, particularly television, may maintain higher levels of perceived credibility and social responsibility.

The findings should be interpreted within the limitations of the study. The research was conducted within the Albanian context, and the questionnaire data are based on respondents' self-reported perceptions. The dynamic nature of social media and continuous changes within digital environments are additional factors that should be considered when interpreting the findings.

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COMPRATIVE ANALYSIS OF STRENGTH AND POWER CHARACTERISTICS ACROSS PICKLEBALL, TENNIS, BADMINTON AND TABLE TENNIS

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Abstract
Background: Strength and power are important determinants of performance in racket sports, but their demands vary according to court dimensions, equipment, movement patterns, and technical requirements. The strength–power profile of Pickleball remains less established than that of Tennis, Badminton, and Table Tennis.
Objective: This study aimed to compare strength and power characteristics across Pickleball, Tennis, Badminton, and Table Tennis and identify sport-specific profiles and evidence gaps.
Methods: A comparative literature review was conducted using primary studies assessing maximal, isometric, explosive, reactive, and sport-specific strength or power. Extracted variables included grip strength, dynamometry, countermovement jump (CMJ), squat jump, reactive strength, lower- and upper-limb power, and sport-specific stroke or ball velocity. Findings were synthesized according to strength domains and sport-specific demands.
Results: All four sports require substantial strength–power capacity, but their dominant characteristics differ. Tennis emphasizes integrated whole-body and upper-limb power during high-velocity strokes. Badminton places strong demands on explosive and reactive lower-limb strength because of repeated lunges, jumps, braking, and rapid directional changes. Table Tennis relies on rapid force production and precise force control. Pickleball appears to require repeated rapid force production, lower-limb power, and neuromuscular control; however, direct quantitative evidence remains limited and is predominantly based on recreational players. Differences in participant characteristics and testing protocols restrict direct quantitative comparisons.
Conclusion: The four racket sports demonstrate distinct strength–power profiles rather than a single strength hierarchy. Standardized studies involving competitive Pickleball players are needed to establish robust cross-sport comparisons.
Keywords: *Pickleball; Tennis; Badminton; Table Tennis; strength; power; racket sports*.

1. Introduction

Racket sports require repeated force production, acceleration, deceleration, changes of direction, and rapid execution of technically demanding strokes. Although Pickleball, Tennis, Badminton, and Table Tennis share these characteristics, differences in court dimensions, equipment, movement patterns, and stroke mechanics result in distinct physical demands. Strength should therefore be considered not only as maximal force production but also as the ability to produce force rapidly and express it through sport-specific movements.

Strength and power are important components of racket-sport performance. In Tennis, physical characteristics such as lower-limb power, grip strength, and upper-body power are associated with competitive performance. Girard and Millet (2009) reported significant relationships between tennis performance and vertical power, grip strength, and plantar-flexor strength in competitive teenage players. Similarly, Ulbricht et al. (2016), in a large sample of 902 junior tennis players, identified serve velocity and upper-body power as important predictors of tennis performance. These findings indicate that tennis performance depends on coordinated expression of strength and power across the kinetic chain.

Badminton and Table Tennis demonstrate different but overlapping strength requirements. Elite Badminton players perform repeated high-intensity movements involving jumping and rapid arm actions. Abián-Vicén et al. (2012) assessed handgrip strength, CMJ height, and CMJ power in 70 players participating in the Spanish National Championship. In Table Tennis, Picabea et al. (2021) reported measurable forearm isometric strength and vertical and horizontal jump performance in 71 national-

category players, while Pradas et al. (2022) demonstrated differences in handgrip strength and vertical-jump performance between elite male and female players.

The evidence for Pickleball remains considerably more limited. Martin et al. (2024) examined 32 recreational doubles players and found no evidence of neuromuscular fatigue based on CMJ performance after repeated match play. Martin et al. (2025) subsequently examined six adult players during a 15-game singles tournament and similarly assessed CMJ-derived neuromuscular responses. These studies provide useful evidence regarding lower-limb neuromuscular responses during Pickleball participation, but they do not establish a comprehensive strength profile involving maximal, isometric, upper-limb, or sport-specific strength.

Previous reviews have demonstrated that strength and power are trainable and functionally important across racket sports. Deng et al. (2022) reported that plyometric training can improve serve velocity, lower-extremity power, sprint performance, and agility in Tennis players, while Deng et al. (2023) found small-to-moderate improvements in muscle strength and power following plyometric training across racket-sport athletes. However, these reviews primarily address training effects rather than direct cross-sport comparisons.

Despite the increasing popularity of Pickleball, a comparative synthesis of maximal/isometric strength, explosive lower-limb power, reactive strength, upper-limb power, and sport-specific power across Pickleball, Tennis, Badminton, and Table Tennis remains limited. Therefore, this study aimed to compare the available evidence on strength and power characteristics across the four racket sports and to identify their principal sport-specific strength–power profiles and current evidence gaps.

2. Methods

2.1. Study design

A comparative literature review was conducted to synthesize empirical evidence on strength and power characteristics in Pickleball, Tennis, Badminton, and Table Tennis. The review followed a structured literature-review approach involving literature identification, appraisal, data extraction, synthesis, and comparative interpretation (Grant & Booth, 2009; Snyder, 2019).

2.2. Literature search

Relevant literature was identified through searches of PubMed/MEDLINE, Scopus, Web of Science Core Collection, and SPORTDiscus. The search covered publications available from database inception to 30 August 2026.

Search concepts combined the four sports with strength- and power-related terms, including “strength,” “muscle strength,” “grip strength,” “isometric strength,” “dynamometry,” “1RM,” “explosive strength,” “power,” “reactive strength,” “countermovement jump,” “squat jump,” “reactive strength index,” “rate of force development,” “serve velocity,” “smash velocity,” and “stroke velocity.”

Additional relevant studies were identified by screening the reference lists of key primary studies and relevant review articles. The overall search and synthesis procedure was informed by established literature-review methodology (Grant & Booth, 2009; Snyder, 2019).

2.3. Eligibility criteria

Studies were considered eligible when they (a) investigated Pickleball, Tennis, Badminton, or Table Tennis players; (b) reported at least one quantitative strength- or power-related outcome; (c) included human participants; and (d) provided sufficient methodological and outcome information for interpretation.

Studies were excluded when they did not involve one of the four target sports, did not assess strength or power, or did not provide sufficient empirical information. Review articles and meta-analyses were used for contextual interpretation and identification of primary studies but were not treated as independent primary datasets.

2.4. Data extraction

The following information was extracted from eligible studies: first author, publication year, DOI, sport, sample size, age, sex, competitive level, study design, strength or power measure, assessment protocol, measurement unit, and principal findings.

When a study reported multiple relevant outcomes, these were retained within the corresponding strength domain without treating each outcome as an independent sample.

2.5. Classification of outcomes

Strength and power outcomes were classified into five domains:

1. Maximal and isometric strength: grip strength, dynamometry, 1RM, and other maximal or isometric force measures;
2. Explosive lower-limb strength and power: CMJ, SJ, jump height, peak force, and peak power;
3. Reactive and eccentric-related strength: RSI, RSImod, braking force, and other stretch-shortening-cycle measures;
4. Upper-limb strength and power: upper-limb strength, medicine-ball throwing, and related power measures; and
5. Sport-specific power: serve velocity, smash velocity, stroke velocity, and other sport-specific expressions of force and power.

CMJ was interpreted as a measure of explosive/stretch-shortening-cycle performance and was not treated as a direct measure of maximal eccentric strength.

2.6. Data synthesis

Because the included studies differed in participant characteristics, competitive level, measurement instruments, and outcome definitions, findings were synthesized descriptively rather than statistically pooled. Mean ± SD values were retained when directly reported by the original studies. No numerical values were estimated or simulated when they were not reported by the original publication.

The comparison focused on sport-specific strength–power profiles rather than establishing a single overall ranking of the four sports. This approach is consistent with the use of comparative and narrative synthesis for heterogeneous literature (Green et al., 2006; Snyder, 2019).

2.7. Quality and interpretation of evidence

The methodological characteristics of individual studies were considered when interpreting the findings, with particular attention to sample size, age, sex, competitive level, study design, and measurement procedures. Because the evidence base was heterogeneous and the review was not designed as a systematic review with formal risk-of-bias scoring, methodological limitations were incorporated into the narrative interpretation rather than converted into a single numerical quality score.

3. Results

3.1. Characteristics of the included studies

The selected studies examined strength and power characteristics in Pickleball, Tennis, Badminton, and Table Tennis. Pickleball evidence remains limited, primarily involving recreational adults and small samples, whereas the other racket sports have a broader evidence base.

Table 1. Characteristics of the main studies

Study	Sport	Sample	Main measures
Martin et al. (2024)	Pickleball	32	CMJ, neuromuscular fatigue
Martin et al. (2025)	Pickleball	6	CMJ, power, RSImod
Girard & Millet (2009)	Tennis	12	Grip strength, jump tests, sprint
Ulbricht et al. (2016)	Tennis	902	Strength, power, speed, serve velocity
Abián-Vicén et al. (2012)	Badminton	70 matches	Grip strength, CMJ, power
Ferreira et al. (2020)	Badminton	—	Upper-limb strength, jump height, shuttle velocity
Picabea et al. (2021)	Table Tennis	71	Forearm strength, CMJ, sprint
Pradas et al. (2022)	Table Tennis	48	Handgrip strength, vertical jump, movement

Note. The sample in Abián-Vicén et al. (2012) comprised 70 matches, not 70 individual players. The sample size for Ferreira et al. (2020) is not reported here.

3.2. Maximal and isometric strength

Evidence on maximal and isometric strength was limited in Pickleball, with the identified studies focusing mainly on countermovement jump (CMJ) outcomes rather than direct maximal-strength tests. In Tennis, grip and plantar-flexor strength were associated with performance in competitive adolescent

players (Girard & Millet, 2009). Badminton and Table Tennis studies also assessed handgrip or forearm strength, indicating the relevance of upper-limb strength in racket sports.

Table 2. Evidence on maximal and isometric strength

Sport	Main measures	Key findings
Pickleball	CMJ-derived measures	Direct maximal-strength evidence remains limited
Tennis	Grip, plantar-flexor strength	Strength measures were associated with performance
Badminton	Handgrip strength	Assessed in elite players
Table Tennis	Handgrip, forearm strength	Assessed alongside physical-performance measures

3.3. Explosive lower-limb strength and power

Explosive lower-limb performance was commonly assessed using CMJ, squat jump, and other jump tests. Pickleball studies reported changes in CMJ-derived outcomes following match play, but their small samples limit generalization. Tennis studies included broader assessments of jumping and sprinting, while Badminton and Table Tennis research also examined jump performance and its relationships with other physical characteristics.

Table 3. Measures of lower-limb explosive strength and power

Sport	Main tests	Evidence
Pickleball	CMJ	Preliminary evidence from recreational and tournament players
Tennis	SJ, CMJ, DJ, sprint	Jump performance assessed alongside speed and strength
Badminton	CMJ, jump power	Explosive performance assessed during match-related research
Table Tennis	Vertical and horizontal jumps	Jump performance assessed in player fitness profiles

3.4. Reactive strength and stretch-shortening-cycle performance

Reactive and stretch-shortening-cycle performance was assessed less consistently than general explosive power. The Pickleball singles study measured RSImod, but its sample comprised only six participants (Martin et al., 2025). Tennis studies included drop-jump and repeated-jump tests. These measures provide information about reactive performance but should not be interpreted as direct measurements of maximal eccentric strength.

Table 4. Evidence on reactive and stretch-shortening-cycle performance

Sport	Measures	Evidence
Pickleball	RSImod, CMJ	Preliminary evidence; very small sample
Tennis	DJ, repeated jumps	Reactive performance assessed directly
Badminton	CMJ-related measures	Indirect evidence of explosive performance
Table Tennis	Vertical jump	Primarily general explosive-performance evidence

3.5. Upper-limb strength and sport-specific power

Upper-limb strength and sport-specific power were examined mainly in Tennis, Badminton, and Table Tennis. Tennis research included serve velocity, while Badminton research examined shuttle velocity during forehand and jump smashes. Pickleball-specific evidence linking upper-limb strength to stroke or serve velocity remains insufficient in the selected studies.

Table 5. Upper-limb strength and sport-specific power

Sport	Measures	Main focus
Pickleball	Limited direct evidence	Stroke-specific strength and power require further study
Tennis	Strength, serve velocity	Relationship between fitness and serving performance
Badminton	Upper-limb strength, smash velocity	Relationships between strength, jumping, and shuttle velocity
Table Tennis	Handgrip, forearm strength	Upper-limb strength within physical-fitness profiles

3.6. Integrated comparison of the evidence

The available literature differs in the range of strength measures, sample sizes, and sport-specific outcomes examined. Pickleball research is currently concentrated on CMJ-derived neuromuscular outcomes, while studies in the other racket sports cover a wider range of strength, jumping, and performance measures.

Table 6. Summary of evidence coverage by strength domain

Strength domain	Pickleball	Tennis	Badminton	Table Tennis
Maximal/isometric strength	Limited	Available	Available	Available
Explosive lower-limb power	Available, preliminary	Available	Available	Available
Reactive strength	Limited	Available	Limited	Limited
Upper-limb strength	Limited	Available	Available	Available
Sport-specific power	Insufficient	Serve velocity	Smash velocity	Limited in selected studies

Note. "Available," "Limited," and "Insufficient" describe the coverage of evidence identified in this review, not the actual strength or performance level of athletes in each sport.

3.7. Summary of results

Overall, the selected literature indicates that strength and power are examined through diverse measures across racket sports. Pickleball research remains preliminary and relies heavily on CMJ-derived outcomes, with limited direct evidence on maximal strength, reactive strength, and sport-specific power. Further studies using larger samples and standardized tests are needed to characterize Pickleball-specific strength demands and enable more robust comparisons with other racket sports.

4. Discussion

4.1. Principal findings

The present comparative review indicates that Pickleball, Tennis, Badminton, and Table Tennis all involve strength and power capacities, but the available evidence suggests different sport-specific profiles. Tennis demonstrates a relatively strong relationship between upper-body power, lower-limb explosive capacity, and sport-specific performance. Badminton combines grip strength and explosive lower-limb power with rapid upper-limb actions. Table Tennis demonstrates measurable isometric grip strength and explosive lower-limb performance despite its smaller playing area. Pickleball also involves lower-limb explosive performance, but direct evidence remains substantially more limited.

4.2. Maximal and isometric strength

Grip strength is one of the most consistently assessed strength variables across the established racket sports. Girard and Millet (2009) found significant relationships between grip strength and Tennis performance in competitive teenage players. In Badminton, Abián-Vicén et al. (2012) demonstrated measurable dominant and non-dominant handgrip strength in elite players. Table Tennis studies have similarly documented handgrip/isometric strength in national and elite players (Picabea et al., 2021; Pradas et al., 2022).

These findings suggest that grip strength is a common physical attribute across racket sports, but its interpretation should remain sport-specific. Maximal grip strength alone does not capture the ability to regulate force during different strokes or transfer force through the kinetic chain.

4.3. Explosive lower-limb strength

Explosive lower-limb performance appears to be a common characteristic across the four sports. Tennis players demonstrate associations between vertical power and competitive performance (Girard & Millet, 2009), while junior Tennis players with higher competitive levels demonstrate better strength- and power-related characteristics (Ulbricht et al., 2016).

Badminton also requires substantial explosive lower-limb performance. Abián-Vicén et al. (2012) reported CMJ and power measures in elite championship players, reflecting the importance of rapid force production during a sport characterized by jumping and rapid movement.

Table Tennis provides an important comparison because its court is substantially smaller, yet national and elite players demonstrate measurable vertical-jump performance (Picabea et al., 2021; Pradas et al., 2022).

For Pickleball, Martin et al. (2024, 2025) provide evidence that CMJ-derived neuromuscular performance can be maintained during repeated match play. However, these studies investigated neuromuscular fatigue rather than establishing normative strength requirements.

4.4. Sport-specific power

Sport-specific power differentiates the four sports more clearly than maximal strength alone. In Tennis, Ulbricht et al. (2016) found that serve velocity and upper-body power were among the most important physical characteristics associated with competitive ranking.

Badminton requires rapid upper-limb force production in combination with lower-limb power. Ferreira et al. (2020) demonstrated relationships among upper-extremity muscle strength, vertical-jump performance, and shuttle velocity during badminton smashes.

In Table Tennis, rapid force production and force control are particularly important because stroke durations and movement distances are short. Picabea et al. (2021) and Pradas et al. (2022) provide evidence of relevant strength and explosive physical capacities in national and elite players.

For Pickleball, however, the current evidence does not provide sufficient quantitative data to establish a direct relationship between strength and paddle or ball velocity. This represents an evidence gap rather than evidence of lower strength requirements.

4.5. Cross-sport interpretation

The evidence does not support ranking Pickleball, Tennis, Badminton, and Table Tennis according to overall strength. Instead, the available studies suggest that each sport emphasizes a particular combination of force, rate of force development, reactive performance, and sport-specific power.

Tennis appears to emphasize integrated whole-body and upper-body power, particularly for serving and stroke production. Badminton requires rapid lower-limb force production and upper-limb power during jumping, lunging, and overhead actions. Table Tennis requires rapid force expression and control within a highly constrained movement environment. Pickleball shares several of these characteristics but currently has a much smaller empirical evidence base.

This interpretation is consistent with broader racket-sport evidence. Deng et al. (2023) reported improvements in strength and power following plyometric training across racket-sport athletes, while Deng et al. (2022) reported improvements in serve velocity, lower-extremity power, sprint performance, and agility in Tennis players. These findings support the trainability and functional importance of strength–power qualities but do not establish a hierarchy among racket sports.

4.6. Limitations of the evidence

The principal limitation is the heterogeneity of the available literature. Studies differed substantially in age, sex, competitive level, sample size, and testing procedures. This limitation is particularly important for Pickleball, where the two identified studies involved only 32 recreational players and six adult tournament players, respectively.

A second limitation is the unequal distribution of outcome measures. Grip strength and CMJ are relatively well represented, whereas IMTP, direct eccentric force, braking force, rate of force development, and standardized sport-specific power measures are much less frequently reported.

Consequently, the absence of evidence for a specific strength characteristic should not be interpreted as evidence that the characteristic is unimportant.

4.7. Research implications

Future Pickleball research should include larger samples of competitive players and standardized strength and power assessments. A comprehensive protocol could include handgrip dynamometry, IMTP, bilateral and unilateral CMJ, RSI/RSImod, eccentric braking force, rate of force development, medicine-ball throws, and paddle/ball velocity.

Cross-sport studies should also match participants by age, sex, body mass, and competitive level. Such standardization would provide a stronger basis for determining whether the strength–power profile of Pickleball is genuinely distinct from Tennis, Badminton, and Table Tennis.

4.8. Overall interpretation

Overall, the evidence supports the view that strength and power are common but sport-specific components of racket-sport performance. Tennis emphasizes integrated whole-body and upper-body power; Badminton combines explosive lower-limb performance with upper-limb strength and power; Table Tennis requires rapid and controlled force production; and Pickleball appears to involve repeated explosive lower-limb actions and neuromuscular control. However, the limited Pickleball evidence prevents a reliable quantitative comparison or overall strength ranking.

5. Conclusion

Pickleball, Tennis, Badminton, and Table Tennis share important strength–power requirements but exhibit distinct patterns of force expression. Tennis demonstrates strong associations between upper-body power, lower-limb explosive capacity, and sport-specific performance; Badminton emphasizes grip strength, explosive lower-limb power, and rapid upper-limb actions; and Table Tennis requires measurable isometric strength and rapid force production. Pickleball also involves lower-limb explosive performance, but the available evidence remains limited and is primarily based on recreational or small-sample populations.

The current literature does not support a reliable ranking of the four sports according to overall strength. Differences in participant characteristics and testing protocols substantially limit direct quantitative comparison. Future research should use standardized strength and power assessments and larger competitive Pickleball samples to establish a more robust sport-specific strength–power profile.

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REAL ESTATE BROKERAGE REGULATION IN THE WESTERN BALKANS: FORMAL CONVERGENCE AND SUBSTANTIVE DIVERGENCE TOWARD EU STANDARDS FOR THE PREVENTION OF MONEY LAUNDERING

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Abstract
This paper examines three interconnected questions regarding real estate brokerage regulation in Albania and the Western Balkans within the context of anti-money laundering (AML) reform. First, it analyses how Albania's Law No. 9/2022 "On the Profession of Real Estate Broker" affects money-laundering prevention in the domestic real estate market. Second, it assesses Albania's readiness for the standards introduced by EU Regulation 2024/1624 (AMLR), which will apply in full from 10 July 2027. Third, it investigates whether real estate brokerage regulation across the Western Balkans (Albania, Serbia, Bosnia and Herzegovina, Montenegro) is converging toward, or diverging from, this evolving European standard. Using a comparative doctrinal method, the study reviews primary legal texts and institutional reports, and constructs a gap-analysis table together with an illustrative regional maturity index. The findings show that Law No. 9/2022 has established the core institutional architecture required for professionalisation-a public registry, mandatory certification, and compulsory AML-related training-but still lacks several operational elements of the AMLR, notably precise monetary thresholds, detailed beneficial-ownership verification procedures, and defined timing for customer due diligence. The regional comparison reveals clear convergence in formal regulatory architecture (registries, examinations, supervision) but persistent divergence in the depth of AML integration within brokerage-specific legislation. The paper concludes that full alignment with the AMLR by 2027 will require a shift from formal professional regulation toward substantive, verifiable AML compliance in daily brokerage practice.

Keywords: real estate brokerage; money laundering; AML/CFT; EU Regulation 2024/1624; Western Balkans.

NUCLEAR WEAPONS AND INTERNATIONAL ORDER: THE PROMISE AND LIMITS OF THE NPT

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Abstract
The proliferation and control of nuclear weapons remain critical challenges to international security and global order. The Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which entered into force in 1970, constitutes the principal multilateral framework for preventing the spread of nuclear weapons, promoting peaceful nuclear cooperation and advancing nuclear disarmament. This article examines the promise and limitations of the NPT within the contemporary international security system. The study adopts a qualitative and analytical research design based primarily on documentary research, drawing on the NPT, United Nations materials, International Atomic Energy Agency (IAEA) documents, Stockholm International Peace Research Institute reports and relevant scholarly literature. The analysis is guided by realism, the security dilemma and game-theoretic perspectives to examine the political, strategic and institutional dimensions of nuclear proliferation and control. The study finds that the NPT has made a substantial contribution to limiting the horizontal spread of nuclear weapons, establishing international norms of nuclear restraint and providing an institutional framework for monitoring nuclear activities through IAEA safeguards. However, its effectiveness remains constrained by persistent nuclear inequality, strategic rivalry, state sovereignty, technological dual-use challenges, difficulties associated with treaty withdrawal, continued modernization of nuclear arsenals and the slow progress towards nuclear disarmament. The analysis further demonstrates that the NPT cannot independently eliminate the security motivations that encourage states to value nuclear capabilities. The study concludes that the NPT remains an indispensable but incomplete instrument of international order. Its long-term credibility and effectiveness depend on strengthening verification, sustaining strategic dialogue, addressing regional security concerns, reducing nuclear risks and achieving meaningful and demonstrable progress towards nuclear disarmament.
Keywords: Nuclear weapons; Non-Proliferation Treaty; arms control; international security; security dilemma; nuclear disarmament; International Atomic Energy Agency; international order

FROM KONYA TO BAGHDAD: RETHINKING SUFI TRADITIONS AS TRANSREGIONAL NETWORKS OF PEACE AND SOCIAL COHESION

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Abstract
This paper explores Sufi orders as transregional networks that historically connected communities, ideas, and institutions across the medieval and early modern Islamicate world. It traces these connections from the formative Sufi milieu of Baghdad to the development of the Mevlevi tradition in Konya, asking how the movement of Sufi scholars, spiritual teachers, disciples, texts, and institutions contributed not only to the circulation of religious knowledge but also to forms of social cohesion and peaceful coexistence. Rather than viewing Sufism primarily as a devotional tradition rooted in particular geographical centres, the paper approaches it as a mobile and relational tradition whose influence was sustained through networks that crossed political, ethnic, and confessional boundaries.
Drawing on classical Sufi biographical dictionaries, hagiographical literature (*manaqib*), *waqf* records, travel accounts, and relevant secondary scholarship in Islamic studies, social network theory, and the anthropology of religion, the study follows intellectual and spiritual connections between Baghdad and Anatolia. Particular attention is given to the legacy of Junayd al-Baghdadi and the ethical and intellectual currents associated with the Baghdad Sufi tradition, and to the ways in which these currents were subsequently reinterpreted within Anatolian Sufism, culminating in the emergence of Jalal al-Din Rumi's Mevlevi tradition in Konya.
The paper further considers the social role of Sufi institutions, particularly *khanqahs*, *zawiyas*, and *tekkes*, as spaces of hospitality, learning, mediation, and community interaction. In periods marked by political fragmentation and upheaval, including the Mongol invasions and the subsequent Seljuk and Ilkhanid transitions, such institutions often brought together people from different ethnic, tribal, and confessional backgrounds. Their importance therefore extended beyond spiritual instruction: they could provide spaces in which relationships were formed, knowledge was exchanged, disputes were mediated, and forms of communal solidarity were sustained.
The paper argues that understanding Sufism through the lens of transregional networks offers a more nuanced account of its historical social and political significance. It also opens a comparative perspective for examining contemporary religious networks and their potential contribution to peacebuilding and social cohesion. At the same time, the study avoids portraying Sufism as inherently peaceful or politically benign. Instead, it emphasises the historical conditions under which Sufi networks could contribute to mediation, coexistence, and social resilience. By bringing together Islamic intellectual history, network theory, and peace studies, the paper ultimately asks how a tradition shaped by mobility, ethical formation, and interpersonal connections might help us rethink the relationship between religious networks and peacebuilding in both historical and contemporary contexts.
Keywords: Sufism; Transregional Networks; Peacebuilding; Social Cohesion; Religious Networks; Baghdad–Konya; Mevlevi Tradition.

DEVELOPING DECISION-MAKING SKILLS IN WOMEN

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Abstract
Developing decision-making skills in women is a key necessity for enhancing their role in personal, familial, social, and professional spheres. Given the structural and cultural challenges and limitations that women face in many societies, strengthening these skills increases their self-efficacy, independence, and capability to manage various life situations.
Effective decision-making involves steps such as problem identification, gathering and analyzing information, evaluating available options, anticipating consequences, and ultimately selecting the best solution while considering individual values and priorities. Training in these skills helps women act with greater confidence in complex situations—including at work, in education, family management, and social participation—and make more informed decisions.
Moreover, developing decision-making abilities in women directly impacts their mental health, reducing feelings of helplessness, boosting self-confidence, and strengthening resilience in the face of challenges. Additionally, women with strong decision-making skills can serve as positive role models and play an effective role in empowering other women.
On a broader level, increasing the number of women with strong decision-making skills leads to a better balance in family and social decision-making processes and paves the way for achieving gender equality and balanced societal development. Investing in this area not only benefits women themselves but also yields widespread advantages for families, society, and future generations.

SOCIAL RESILIENCE TRAINING FOR ACTIVE WOMEN

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Abstract
Social resilience training for active women is a fundamental approach to enhancing the individual and collective capabilities of women in confronting social, economic, and cultural challenges. Due to the multiple roles active women undertake in family, community, and workplace environments, they are more exposed than other groups to psychological pressures, social discrimination, job insecurity, and social crises. In this context, social resilience—defined as the ability to adapt, withstand, and recover in the face of difficult conditions—plays a key role in preserving women's mental health and social stability.
Social resilience training involves strengthening skills such as stress management, problem-solving, informed decision-making, effective communication, self-awareness, and social participation. These trainings enable women to demonstrate more logical and constructive responses during crises and to leverage their individual and social capacities to overcome challenges. Furthermore, enhancing social resilience increases self-confidence, a sense of social belonging, and the motivation for active participation in social processes among women.
On the other hand, resilient women can act as agents of change in society and play an effective role in strengthening social cohesion, reducing social harms, and transmitting coping skills to future generations. Social resilience training for active women not only contributes to improving their individual quality of life but also lays the groundwork for sustainable development, increases social capital, and fosters a society more resistant to crises.

FROM INFORMATION CONSUMERS TO CRITICAL AI CITIZENS: RETHINKING MEDIA AND EDUCATION IN THE AGE OF GENERATIVE ARTIFICIAL INTELLIGENCE

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Abstract
The rapid development of Generative Artificial Intelligence (GenAI) is fundamentally transforming the ways in which individuals access, produce, evaluate, and disseminate information. While AI-powered tools offer unprecedented opportunities for education, communication, and knowledge creation, they also introduce complex challenges related to misinformation, algorithmic bias, synthetic content, information credibility, and the erosion of critical thinking. In this rapidly changing environment, traditional concepts of media literacy and digital literacy are no longer sufficient to prepare individuals to navigate an increasingly AI-mediated information ecosystem.
This study examines the intersection of media, education, and Generative AI, with a particular focus on the transition from passive information consumption toward the development of critical AI citizens. It argues that education systems and media institutions share a growing responsibility to equip individuals with the knowledge and competencies required not only to use AI effectively, but also to question, evaluate, verify, and critically interpret AI-generated information. The study explores how media and educational practices can contribute to developing critical AI literacy, strengthening information verification skills, and preserving human judgment and intellectual autonomy in the age of intelligent technologies.
The research adopts a conceptual and analytical approach, drawing on contemporary literature concerning AI literacy, media and information literacy, critical thinking, digital citizenship, and Generative AI in education and communication. It proposes an integrated conceptual framework connecting AI literacy, media literacy, critical thinking, information verification, and responsible digital citizenship. The study further highlights the need for educational curricula and media practices to move beyond teaching individuals how to operate AI tools toward teaching them how to critically interrogate the outputs, sources, assumptions, and potential biases embedded in AI-generated content.
The study concludes that the central challenge of the AI era is not merely ensuring that individuals can use intelligent technologies, but ensuring that they remain capable of thinking independently in environments increasingly shaped by machines. Building critical AI citizens therefore requires a renewed partnership between education and media, where both become essential pillars for developing informed, skeptical, responsible, and intellectually autonomous citizens.

Keywords: Generative Artificial Intelligence; AI Literacy; Media Literacy; Media and Information Literacy; Critical Thinking; Information Verification; Digital Citizenship; Education; Misinformation; Human-AI Interaction.

THE EFFECT OF MOTIVATION ON PRIMARY SCHOOL TEACHERS PERFORMANCE IN RAFI LOCAL GOVERNMENT EDUCATION AUTHORITY OF NIGER STATE

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Abstract
This study assessed the effect of motivation on the performance of primary school teachers in Rafi Local Government Education Authority, Niger State. A survey research design was adopted. The target population comprised 1,321 public primary school teachers, from which a sample of 332 respondents was selected using the Krejcie and Morgan sample size determination table with an additional 10% to account for non-response. Data were collected using a structured questionnaire and analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM) with SmartPLS 4. The findings indicate that motivation significantly enhances teachers' performance in Rafi Local Government Education Authority, Niger State, suggesting that improving motivational factors such as compensation, promotion, recognition, and job security can positively influence teachers' effectiveness and overall job performance. It recommended that the Niger State Universal Basic Education Board (NSUBEB) and Rafi Local Government Education Authority should strengthen teacher motivation through prompt salary payment, timely promotion, recognition of outstanding performance, improved working conditions, and enhanced job security to improve the quality of primary education.
Keywords: Motivation, Teachers' Performance, Primary School Teachers.

1.1 Introduction

The motivation and performance of teachers are pivotal elements in the educational process, influencing student outcomes and the overall quality of education. The educational system worldwide has increasingly recognized the need to address teachers' motivation to ensure effective teaching and learning. Teacher motivation, in terms of intrinsic and extrinsic factors, directly correlates with their performance, which in turn affects the broader educational goals of academic achievement and societal development (Ryan, & Deci, 2020). Globally, education policy frameworks have stressed the importance of creating conducive environments for teachers, including adequate compensation, professional development, and work-life balance, in order to enhance their motivation and performance (Joseph, 2022).

In many countries, educational policies are designed to address the critical role of teachers. International organizations such as UNESCO and the World Bank have highlighted teacher motivation as a central element in improving education quality (Elfert, 2021). For instance, in its Education 2030 Framework for Action, UNESCO advocates for policy reforms that support teacher quality through improved recruitment, training, retention, and working conditions. These global policies emphasize the need for governments to adopt strategies that enhance teacher satisfaction, as a motivated teacher is more likely to deliver high-quality education, fostering a positive impact on students' academic performance (Omollo, 2023).

In Africa, teacher motivation remains a critical issue, with various challenges such as inadequate pay, lack of professional development opportunities, and poor working conditions often cited as key barriers to effective teaching (Plessis, & Mestry, 2019). The African Union's Continental Education Strategy for

Africa (CESA 16-25) acknowledges the importance of teacher quality and motivation in achieving the goals of educational development across the continent. While several African nations have made strides toward improving the conditions of teachers, substantial challenges persist, particularly in rural and underserved areas where teacher shortages and low morale are prevalent. According to a report by the African Development Bank, the lack of incentives for teachers in these regions has been linked to high rates of absenteeism, low productivity, and poor student performance (Rwigema, 2022).

In Nigeria, the educational system is similarly grappling with issues of teacher motivation. Despite the country's substantial investments in education, teachers often face challenges such as low salaries, lack of proper teaching resources, and inadequate professional development programs (Muremela, Kutame, Kapueja, & Ajani, 2023). The National Policy on Education, first introduced in 1977 and revised multiple times since, recognizes the need for improving teacher quality and performance but struggles with implementation. The Nigerian government has made efforts to address teacher-related issues through initiatives such as the Teachers' Registration Council of Nigeria (TRCN), which aims to standardize teacher qualifications and professional conduct (Afolabi 2021).

At the state level, Niger State, like many other Nigerian states, faces its own unique set of challenges related to teacher motivation. Teachers in Niger State, particularly in rural areas, experience poor infrastructure, limited access to professional development opportunities, and delays in salary payments (Murugaiah, 2023). The Niger State Ministry of Education has periodically launched initiatives aimed at improving the quality of education, but these efforts are often underfunded or poorly implemented. Moreover, the state's reliance on external funding for educational programs complicates long-term sustainability.

Adequate compensation, including prompt payment of salaries and allowances, enhances teachers' morale, reduces financial stress, and encourages greater dedication to instructional duties (Mogboh, 2025). Similarly, regular and merit-based job promotion serves as recognition of teachers' efforts, increases job satisfaction, and motivates them to improve their professional performance. Job security also plays a vital role by assuring teachers of stable employment, fostering confidence, commitment, and loyalty to the education system. When teachers perceive their compensation to be fair, promotion processes to be transparent, and their jobs to be secure, they are more likely to demonstrate higher levels of instructional effectiveness, punctuality, classroom management, and overall job performance (Yusuf, Sani, Namiji, & Mohammed, 2025). These motivational factors are therefore essential for improving the quality of primary education in Nigeria, particularly in rural areas such as Rafi Local Government Education Authority of Niger State.

Within Rafi Local Government Education Authority (LGEA), these challenges are particularly pronounced due to the predominantly rural nature of the area. Many primary school teachers work under difficult conditions characterized by inadequate classroom facilities, insufficient teaching and learning materials, long commuting distances, limited access to in-service training, and inadequate incentives. In addition, the geographical dispersion of schools and the socio-economic conditions of many communities further complicate effective service delivery and teacher supervision (Ibrahim 2025). These conditions have the potential to diminish teachers' morale, commitment, and job satisfaction, thereby adversely affecting their instructional effectiveness and overall performance. It is therefore important to investigate the assessment of the effect of motivation on primary school teachers' performance in rafi Local Government education authority of Niger state.

1.2 Statement of the Research Problem

The quality of education is a key indicator of national development, with teachers playing a central role in achieving educational goals (Ilham & Imay Syahrah, 2018; UNESCO, 2023). However, in Nigeria, inadequate salaries, poor working conditions, insufficient instructional materials, and limited educational facilities continue to undermine teachers' motivation and job performance, while the ineffective implementation of motivational strategies has further reduced their commitment and productivity (Musa, 2018; Nigeria Union of Teachers [NUT], Niger State Wing, 2024). Despite various interventions by the Niger State Government, the Niger State Universal Basic Education Board (NSUBEB), the Universal Basic Education Commission (UBEC), and development partners to improve the quality of basic education in Rafi Local Government Area of Niger State, significant challenges continue to affect teachers' motivation and performance (UBEC, 2023; NSUBEB, 2024). These interventions include the rehabilitation and construction of school infrastructure, teacher capacity-

building programmes, the provision of instructional materials, and the strengthening of School-Based Management Committees (SBMCs) to promote community participation in school management (Federal Ministry of Education [FME], 2021; UBEC, 2023). However, many primary school teachers in Kagara and other communities continue to experience persistent challenges, including irregular or delayed payment of salaries and allowances, limited opportunities for promotion, inadequate recognition and rewards, insufficient teaching and learning facilities, and restricted access to continuous professional development programmes, all of which adversely affect their motivation and job performance (Adedeji & Owoeye, 2018; Muremela et al., 2023). In addition, concerns over job security and safety have become more pronounced due to the insecurity experienced in Rafi Local Government Area. Kagara gained national attention following the abduction of students and staff from Government Science College, Kagara, in February 2021, an incident that exposed the vulnerability of educational institutions in the area (UNICEF, 2021; BBC News, 2021). Although government security interventions have improved the situation in recent years, many schools, particularly those in remote communities, continue to operate under difficult conditions (International Crisis Group, 2022). These challenges have contributed to low teacher morale, reduced commitment, absenteeism, and declining instructional effectiveness (UNESCO, 2023; Muremela et al., 2023).

The Nigeria Union of Teachers (NUT), Niger State Wing, reported that poor remuneration, inadequate welfare, insufficient teaching materials, and poor educational infrastructure have contributed to the increasing exit of teachers from public schools in Niger State. The union also noted the incomplete implementation of the Teachers' Salary Scale (TSS) and the ₦80,000 minimum wage, resulting in low morale, job dissatisfaction, delayed promotion, reduced commitment, and poor job performance among teachers (NUT, Niger State Wing, 2024; Daily Trust, 2024; Adedeji & Owoeye, 2018; UNESCO, 2023). Against this backdrop, the study seeks to find answers to the following questions.

1.2 Research question

To what extent has as motivation affect primary school teachers' performance in rafi local government education authority of Niger State.

1.3 Objective of the Study

To examine the effect of motivation on primary school teachers' performance in rafi local government education authority of Niger State.

1.4 Hypothesis of the Study

Motivation has no significant effect on primary school teachers' performance in rafi local government education authority of Niger State.

2.1 Literature Review and Theoretical Framework

2.1.1 Concept of Motivation

Ryan and Deci (2020) defined motivation as the psychological energy that initiates, directs, and sustains goal-oriented behaviour, emphasizing that it explains why individuals choose to act and the intensity and persistence of their efforts in pursuing desired outcomes. Similarly, Schunk and DiBenedetto (2020) described motivation as the process through which goal-directed activities are initiated and sustained over time, noting that it determines the direction, persistence, and intensity of an individual's behaviour. Latham (2017) viewed motivation as the internal psychological process that stimulates individuals to act toward achieving specific goals, arguing that it determines the direction, effort, and persistence of behaviour. Robbins and Judge (2023) defined motivation as the processes that account for an individual's intensity, direction, and persistence of effort toward attaining a goal, stressing that motivated employees exert greater effort to achieve organizational objectives. In a similar vein, Armstrong (2020) regarded motivation as the factors that influence people to behave in particular ways in order to achieve desired goals and satisfy both personal and organizational needs. Mullins (2019) also described motivation as the driving force that encourages individuals to exert effort toward accomplishing organizational and personal objectives, emphasizing that motivation determines employees' willingness to perform effectively within an organization.

2.1.2 Concept of Teachers' Performance

Teachers' performance has been conceptualized by different scholars as the degree to which teachers effectively discharge their instructional, professional, and administrative responsibilities to achieve

educational goals and improve learners' academic outcomes. According to UNESCO (2023), teachers' performance refers to the extent to which teachers effectively carry out their instructional, professional, and administrative duties to enhance students' learning outcomes and achieve educational objectives. Similarly, the Organisation for Economic Co-operation and Development (OECD, 2023) defines teachers' performance as the ability of teachers to plan lessons, deliver effective instruction, manage classrooms, assess learners, and perform other professional responsibilities in accordance with established educational standards. Ibrahim and Yusuf (2024) further describe teachers' performance as the degree to which teachers demonstrate competence, commitment, punctuality, instructional effectiveness, and adherence to professional ethics in the teaching and learning process. Furthermore, Adu, Adebayo, and Oladipo (2023) view teachers' performance as the successful execution of teaching responsibilities that lead to improved student achievement, effective classroom management, and the attainment of curriculum objectives.

2.1.3 Empirical Review of the Study

Adedeji and Owoeye (2018) investigated the influence of motivational strategies on teachers' job performance in public primary schools in Ekiti State, Nigeria. The study adopted a descriptive survey research design involving 250 primary school teachers selected through simple random sampling. Multiple regression analysis was employed to analyse the data collected. The findings revealed that salary, recognition, effective supervision, and opportunities for professional development significantly predicted teachers' job performance. Among these motivational strategies, recognition emerged as one of the strongest predictors of instructional effectiveness. The study concluded that enhancing teachers' motivation would significantly improve their classroom performance and overall educational productivity.

Nwosu and Okeke (2017) examined the relationship between motivation and teachers' effectiveness among primary school teachers in Anambra State, Nigeria. The study employed a descriptive survey research design involving 310 teachers selected through stratified sampling techniques. Data were analysed using Pearson correlation and regression analysis. The findings indicated that teachers' motivation had a significant positive influence on lesson preparation, classroom management, instructional delivery, and pupils' academic performance. The researchers recommended improved welfare schemes, timely promotion, and effective recognition systems as strategies for sustaining teachers' motivation and enhancing their effectiveness.

Yusuf and Adigun (2010) investigated the relationship between teachers' motivation and job performance among public primary school teachers in Kwara State, Nigeria. The study adopted a correlational research design and administered questionnaires to 280 teachers. Pearson correlation and regression analyses were used to analyse the data. The findings revealed a significant positive relationship between teacher motivation and classroom effectiveness. Teachers who received financial incentives, timely promotions, and adequate recognition performed better in instructional delivery, classroom discipline, pupil assessment, and other teaching responsibilities than those with lower levels of motivation. The study concluded that improved motivational incentives are fundamental to enhancing teachers' job performance in public primary schools.

Richardson and Watt (2010) investigated teachers' motivation and its influence on professional commitment and performance among beginning teachers in Australia. The study employed a survey research design involving 1,653 participants and utilized the Factors Influencing Teaching Choice (FIT-Choice) Scale for data collection. Structural Equation Modelling (SEM) was used for data analysis. The findings indicated that teachers who were intrinsically motivated exhibited greater commitment, higher classroom effectiveness, and increased job satisfaction compared with those who were primarily motivated by extrinsic rewards. The researchers concluded that intrinsic motivation is a significant predictor of teacher performance and long-term retention in the teaching profession.

Akinfolarin and Ehinola (2014) conducted a study on motivation and teachers' job performance among public secondary school teachers in Ondo State, Nigeria. The study adopted a descriptive survey research design and collected data from 320 teachers using structured questionnaires. Data were analysed using the Pearson Product Moment Correlation technique. The findings revealed a significant positive relationship between motivation and teachers' job performance. Teachers who received prompt salaries, timely promotions, recognition, and opportunities for professional development demonstrated

higher instructional effectiveness than their counterparts. The study recommended that government and school administrators should improve teachers' motivational packages to enhance their performance.

2.3 Theoretical framework

Herzberg's Two-Factor Theory of Motivation (Frederick Herzberg, 1959)
Herzberg's Two-Factor Theory, also known as the Motivation–Hygiene Theory, explains that employees' job satisfaction and dissatisfaction are influenced by two distinct categories of factors: motivators (intrinsic factors such as achievement, recognition, and responsibility), which enhance satisfaction and performance, and hygiene factors (extrinsic factors such as salary, working conditions, and job security), which prevent dissatisfaction but do not necessarily motivate employees. The theory serves as the foundation for this study by explaining how both intrinsic and extrinsic motivational factors influence teachers' performance.

Assumptions of the Theory
Herzberg's Two-Factor Theory assumes that job satisfaction and dissatisfaction are influenced by different factors. Intrinsic or motivator factors, such as achievement, recognition, responsibility, and career advancement, enhance employees' motivation and performance, while extrinsic or hygiene factors, including salary, working conditions, supervision, and job security, prevent dissatisfaction but do not necessarily motivate employees. The theory further suggests that organizations achieve higher productivity when they adequately address both intrinsic and extrinsic employee needs.

Criticisms of the Theory
Despite its significance, Herzberg's Two-Factor Theory has several limitations. It assumes that all employees are motivated by the same factors, although motivational needs differ across individuals and contexts. The distinction between motivators and hygiene factors is often unclear, as factors like salary and promotion may serve both roles. Additionally, the theory was developed using professionals, limiting its applicability to other occupations, including teachers. It also gives limited attention to external factors such as economic conditions and government policies, and some empirical studies have reported inconsistent findings regarding the separation of motivator and hygiene factors.

Relevance of the Theory to the Study
Herzberg's Two-Factor Theory is relevant to this study because it explains how both intrinsic factors (such as recognition, promotion, responsibility, and professional growth) and extrinsic factors (such as salary, job security, supervision, and working conditions) influence teachers' motivation and performance. The theory provides a suitable framework for examining the effect of motivation on primary school teachers' commitment, instructional delivery, classroom management, lesson preparation, punctuality, and overall job performance in Rafi Local Government Education Authority, Niger State. It also offers practical insights for educational policymakers and administrators on improving teachers' welfare and motivation to enhance the quality of primary education.

3.1 Methodology
This study adopted a survey research design, which was considered appropriate for obtaining quantitative data from respondents through the use of structured questionnaires. Primary data were collected using questionnaires, while secondary data were obtained from relevant textbooks, journal articles, government publications, and other published sources. The target population comprised all 1,321 public primary school teachers in Rafi Local Government Education Authority, Niger State, as reported by the Niger State Universal Basic Education Board (NSUBEB, 2024). A sample size of 302 respondents was determined using the Krejcie and Morgan (1970) sample size determination table. To account for possible non-response and incomplete questionnaires, an additional 10% was added to the calculated sample, following the recommendation of Israel (2013), resulting in a final sample size of 332 respondents. Respondents were selected using the simple random sampling technique to ensure that each teacher had an equal chance of being included in the study. Data were analysed using Smart PLS 4, where descriptive statistics were employed to summarize the data, while the Partial Least Squares Structural Equation Modelling (PLS-SEM) technique was used to test the study hypotheses and examine the relationships among the study variables.

3.1.1 Measurement of Variables

The motivation is assessed using four items from the measurement scale, with each item rated on a five-point Likert scale. Similarly, primary school teachers performance is evaluated using five items, also rated on a five-point Likert scale.

The structural model assessed individual item reliability, internal consistency reliability, and discriminant validity. Firstly, the individual item reliability was assessed by examining the outer loadings of each construct's measure (Hair et al., 2017). This is depicted in the figure 1 below:

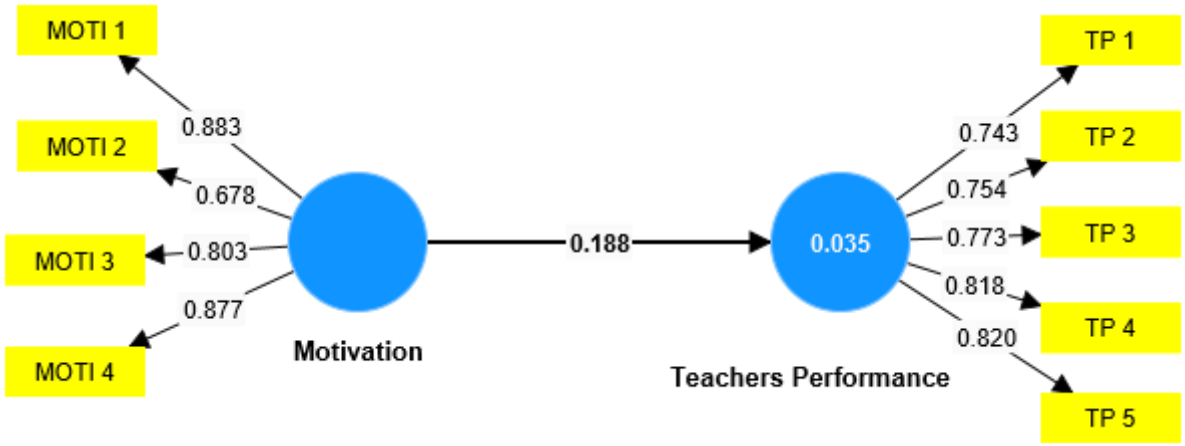


Figure 1: Measurement Model

the measurement model demonstrates that the factor loadings for each construct meet the minimum threshold for individual item reliability. To evaluate internal consistency, this study utilizes composite reliability (CR), in line with the recommendation by Hair et al. (2019) that a CR value of 0.60 or higher indicates acceptable reliability. As shown in Table 1, the CR values range from 0.864 to 0.867, confirming strong internal consistency. Additionally, convergent validity was assessed using the Average Variance Extracted (AVE). According to Hair et al. (2017), an AVE value of 0.50 or above is considered acceptable. Table 1 indicates that all constructs exceed this threshold, thereby confirming adequate convergent validity.

Table 1 Construct reliability and validity

Construct	Composite reliability	Average variance extracted
MOTI	0.864	0.664
TP	0.867	0.612

Table 1 shows that both Motivation (MOTI) and Teachers Performance (TP) demonstrate strong reliability and convergent validity, as their composite reliability and average variance extracted values exceed the recommended thresholds, confirming the consistency and validity of the measurement model.

Table 2: Measurement Model: Discriminant Validity (Fornell and Larcker)

Construct	MOTI	TP
Motivation	**0.815**	
Teachers Performance	**0.188**	**0.782**

Table 2 shows that the square root of the AVE for Motivation (0.815) and Teachers' Performance (0.782) is greater than the correlation between the two constructs (0.188**).** This satisfies the Fornell and Larcker

criterion**,** confirming adequate discriminant validity. Therefore, the constructs are distinct and measure different concepts in the measurement model.

Table 3 Heterotrait-Monotrait Ratio (HTMT)

Table 3: Discriminant Validity (HTMT)

Construct	MOTI	TP
Motivation		
Teachers Performance	**0.208**	

Table 3 presents the discriminant validity results using the Heterotrait-Monotrait Ratio (HTMT) for the study variables. The diagonal bold figures represent the square root of the AVE, all of which fall within the acceptable threshold. This confirms that the study meets the required criterion for discriminant validity.

R-Squared The coefficient of determination (R2) illustrates the amount of variance in the endogenous constructs. It indicates that the threshold value of 0.25 (as weak), 0.5 (as moderate) and 0.7 (as substantial respectively) (Chin 1998). Thus, below is the R square value for the study.

Table 4: Coefficient of Determination

R Square	R -Square	R-Square Adjusted
Teachers Performance	0.035	0.033

Table 4 presents the coefficient of determination (R^2) and the adjusted R^2 for the model predicting Teachers' Performance. The R^2 value of 0.035 indicates that 3.5% of the variation in teachers' performance is explained by the independent variable(s) included in the model. The adjusted R^2 value of 0.033 shows a slight reduction after adjusting for the number of predictors, suggesting that the model has minimal bias due to the number of explanatory variables. This finding indicates that the predictor(s) included in the model have a weak explanatory power, accounting for only a small proportion of the variation in teachers' performance. The remaining 96.5% of the variation in teachers' performance is attributable to other factors not included in the model, indicating that additional variables may be important in explaining teachers' performance.

Structural Model

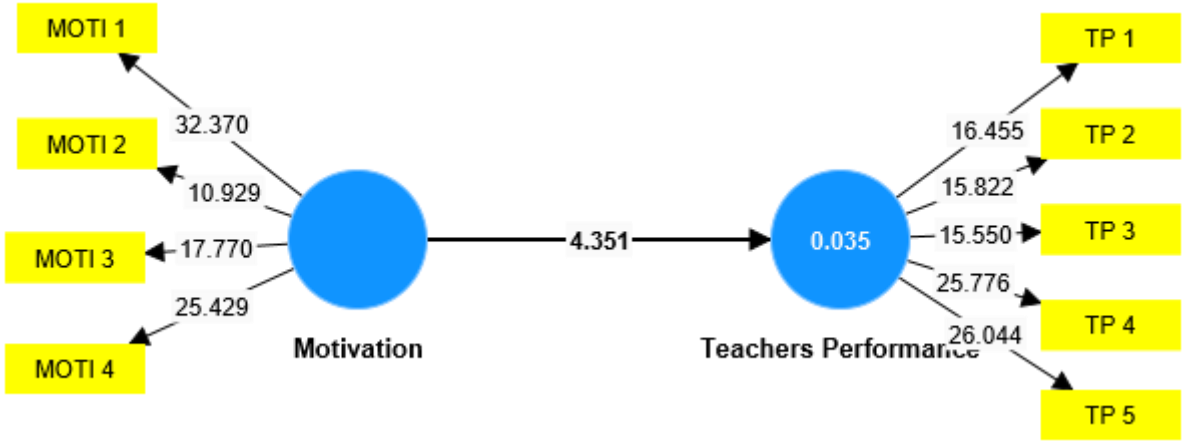


Table 5 **Hypotheses test**

Hyp	Construct	Beta	Standard deviation	T statistics	P values	Decision
HO	MOTI-> TP	0.202	0.043	4.351	0.000	Rejected

Table 2 presents the results of the hypothesis test examining the effect of Motivation (MOTI) on Teachers' Performance (TP). The results show that motivation has a positive and statistically significant effect on teachers' performance, with a path coefficient (β) of 0.202, indicating that an increase in motivation leads to a corresponding improvement in teachers' performance. The t-statistic of 4.351 exceeds the critical value of 1.96, while the p-value of 0.000 is less than the 0.05 level of significance, confirming that the relationship is statistically significant. Therefore, the null hypothesis (H_0), which states that motivation has no significant effect on teachers' performance, is rejected.

Summary of Finding

This finding implies that motivation significantly enhances teachers' performance in Rafi Local Government Education Authority, Niger State, suggesting that improving motivational factors such as compensation, promotion, recognition, and job security can positively influence teachers' effectiveness and overall job performance.

Conclusion

Based on the findings of the study, it is concluded that motivation has a positive and significant effect on the performance of primary school teachers in Rafi Local Government Education Authority, Niger State. The study established that motivational factors such as adequate compensation, timely promotion, recognition, job security, and supportive working conditions enhance teachers' commitment, instructional effectiveness, classroom management, punctuality, and overall job performance. The findings therefore underscore the importance of improving teachers' motivation as a strategy for enhancing the quality of teaching and learning in public primary schools.

Recommendation

The Niger State Universal Basic Education Board (NSUBEB) and Rafi Local Government Education Authority should strengthen teachers' motivation by ensuring prompt payment of salaries, implementing timely and merit-based promotions, providing adequate recognition, guaranteeing job security, and improving working conditions, as these measures will enhance teachers' commitment, instructional effectiveness, and overall job performance in public primary schools.

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4-WEEK STEP-BY-STEP PLANNER TO WRITE A RESEARCH ARTICLE/PAPER AS A PROFESSIONAL

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Abstract
Writing a research article requires sustained attention, careful planning, and the ability to manage several interconnected tasks within a limited period. This paper proposes a structured four-week workflow for developing a research article from the initial research question to final submission. The planner divides the process into 20 focused working days, with approximately 69 hours allocated to research design, literature engagement, analysis, writing, revision, and submission preparation. During the first week, researchers define the research question, identify a target journal, organise relevant literature, examine methodological gaps, draft the Methods section, and prepare the analysis, tables, and figures. The second week focuses on reporting findings and developing the Introduction, literature review, theoretical framework, and Discussion. The third week is devoted to completing the Conclusion, drafting the abstract, refining the title and keywords, and improving the coherence and readability of the full manuscript. The final week emphasises language editing, reference and formatting checks, feedback from colleagues or supervisors, substantive revision, and preparation of the cover letter. The workflow also identifies appropriate digital tools for literature discovery, reference management, writing assistance, data presentation, and proofreading. Rather than treating academic writing as a single final-stage activity, the planner presents it as a gradual and manageable process involving repeated cycles of drafting, evaluation, and refinement. This practical framework may help researchers maintain momentum, reduce uncertainty, and produce a more coherent manuscript within a clearly defined timeframe.
Keywords: Research writing; Article development; Academic productivity; Literature review; Manuscript planning

UNIVERSITY-INDUSTRY LINKAGE AND KNOWLEDGE TRANSFER

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Abstract
The linkage between university and the productive sector constitutes a relevant mechanism for promoting the generation, exchange, and transfer of knowledge to the economic and social environment. In this context, universities face the challenge of strengthening their institutional capacities and establishing collaboration mechanisms that allow knowledge generated through research to transcend the academic sphere and contribute to addressing the needs of the productive sector. The objective of this study is to analyze the scientific literature on university-industry linkage and its relationship with knowledge transfer processes, identifying the main mechanisms, associated factors, and challenges. A documentary review of scientific literature published in recent years was conducted, considering studies related to university-industry collaboration, knowledge transfer, and mechanisms of interaction with the productive sector. The results show that linkage is a multidimensional process involving institutional and organizational factors. Among the main mechanisms identified are collaborative research projects, the provision of specialized services, researcher mobility, human resource development, and innovation and entrepreneurship activities. Likewise, institutional capacity, university policies, incentives, and the existence of support structures play an important role in facilitating knowledge transfer. It is concluded that strengthening university-industry linkage requires moving beyond a vision focused exclusively on knowledge generation and advancing toward strategies that promote its exchange, application, and utilization in the productive sector.
Keywords: University; Knowledge management; Collaboration; Knowledge transfer.

GLOBAL CONFLICTS AND THE CRISIS OF INTERNATIONAL LAW: CHALLENGES TO HUMAN RIGHTS, PEACE AND ACCOUNTABILITY

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Abstract
Abstract Structural limitations have emerged in the workings of the current international legal order in recent conflicts, which add to a scholarly, diplomatic, and political debate about the role international law plays in controlling behaviour of states and safeguarding vulnerable populations. In this article, the following cumulative human rights protection, peace-building and security building and accountability for atrocity crimes challenges to international law are explored as part of the perception of the crisis of international law.As part of the perception of the international law disaster, the following overlapping human rights protection, international peace and security maintenance, and international accountability for atrocity crimes challenges are examined in this article. The study takes a doctrinal and analytical research methodology and examines the normative frameworks, such as the norms on the use of force, international humanitarian law, and international human rights law, which regulate the use of force,while looking at the institutional machinery which supports and enforce these rules of law with particular emphasis on the United Nations Security Council, the International Court of Justice, and the International Criminal The analysis suggests that the current crisis is one of implementation and enforcement, including the paralysis of the Security Council to effectively act against grave violations in some conflicts, and limitations of jurisdiction and cooperation of international courts, as well as political engineering of impunity. These interlocking dynamics have a negative effect on state compliance, infuse a growing degree of doubt and failure into treaty regimes, and ultimately on the credibility of human rights assurance to victims. The article illustrates that as per current practice, in many cases despite inequality, there are accountability mechanisms that work effectively when powerful states refuse to cooperate, as witnessed in situations of Ukraine and Gaza. Finally, the article suggests some achievable steps toward reform such as increasing domestic complementarity, expanding the implementation of universal jurisdiction, Security Council reform discussions, and new responsibilities for regional institutions, civil society, and independent investigative efforts, all of which could form the basis for consistent, incremental institutional reforms necessary to maintain the order of the rule. The results would interest both academics who are interested in the legal-philosophical issues and policymakers and practitioners who want to balance the legal obligation with the political reality in a pluralistic environment.
Keywords: international law, human rights, accountability, International Criminal Court, United Nations Security Council, armed conflict.

THE NONLINEAR CONNECTION BETWEEN INFLATION ON INCOME/WEALTH INEQUALITY IN THE EUROPEAN UNION. MEDIATED EFFECTS AND MODERATED MEDIATION MODELS

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Abstract
The COVID-19 pandemic amplified economic challenges like income and wealth inequality and inflation, necessitating careful policy attention. While the link between inflation and income inequality is well-studied, this research addresses a gap by investigating the non-linear relationship between inflation and income/wealth inequality, using Gini index and top and bottom shares in the EU from 1990-2024. Employing Continuously-Updated and Bias-Corrected (CUP-BC) estimators and system Generalized Method of Moment (system GMM) estimators to account for endogeneity, the study finds a U-shaped association between inflation and Gini index, but also between inflation and the income and wealth shares of both the top and bottom for the EU. The study also reveals the mediating role of self-employment in the relationship between inflation and the top 1% and 10% income/wealth share and the moderating effect of credit on the mediation of self-employment on the top 1% and top 10% income/wealth inequality.
Keywords: inflation, income inequality, wealth inequality, self-employment, immigrants.

FROM ENERGY ACCESS TO PRODUCTIVITY: DOES TECHNOLOGICAL INNOVATION MATTER ACROSS SECTORS IN SUB-SAHARAN AFRICA?

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Abstract
Energy poverty remains a primary structural constraint on economic performance in Sub-Saharan Africa (SSA), yet its impacts vary significantly across economic sectors. Deficits in electricity and clean energy infrastructure inflate production overheads, hinder modern technology adoption, and induce operational inefficiencies. This paper investigates the empirical impact of multidimensional energy access (electricity and clean fuels) on sectoral productivity across 38 Sub-Saharan African economies over the period 2000–2022. Utilizing Fixed Effects (FE), Instrumental Variable Generalized Method of Moments (IV-GMM), and Panel Quantile Regressions, we evaluate the direct, moderated, and non-linear dynamics of energy access on agricultural, industrial, and service sector productivity. Findings demonstrate that linear electricity access alone fails to generate statistically significant productivity gains across all sectors, whereas access to clean cooking fuels directly enhances service sector productivity. However, technological innovation acts as a potent moderating catalyst: the interaction between technological advancement and energy access yields robust, statistically significant productivity gains in agriculture. Furthermore, polynomial estimation uncovers a significant threshold effect, indicating that industrial and service sector productivity benefits emerge only after national electricity access exceeds 47.3%. Quantile regressions confirm substantial conditional distribution heterogeneity across SSA economies. Policy interventions must move beyond simple electrification targets to integrate energy infrastructure with sector-specific technological adoption strategies.
Keywords: Energy Poverty; Energy Access; Sectoral Productivity; Technological Innovation; Panel GMM; Sub-Saharan Africa.
JEL Classification: D24; O33; O55; Q42; Q43.

1. Introduction

1.1 Background of the study

The development challenge confronting Sub-Saharan Africa is no longer adequately described as a problem of insufficient resources (International Energy Agency, 2023). The region possesses substantial agricultural land, mineral resources, a rapidly expanding labour force, considerable renewable-energy potential and increasingly connected markets. The more fundamental challenge is the region's limited ability to convert these resources into sustained productivity growth (Araoye & Yusuf, 2025). Energy infrastructure is central to this problem because virtually every modern production process depends, directly or indirectly, on reliable energy.

Electricity powers irrigation systems, cold storage, agro-processing machinery, manufacturing equipment, information systems, telecommunications infrastructure, commercial establishments and increasingly digital production (Andersen & Dalgaard, 2013). Clean fuels and technologies similarly influence the efficiency with which households and businesses perform cooking, heating and other energy-intensive activities. Where energy is unavailable, unreliable or prohibitively expensive, firms and households are forced to operate below productive capacity, rely on inefficient technologies or substitute labour and capital for missing energy services (Geginat & Ramalho, 2018; Yusuf, 2025).

The problem is particularly pronounced in SSA. World Bank data continue to show substantial variation in electricity access across the region, with the aggregate SSA economy still characterised by a large access deficit. More importantly, access statistics do not necessarily capture the quality, reliability or productive usefulness of electricity (Yusuf & Saka, 2026). A connection to the grid does not guarantee continuous supply, adequate voltage, affordability or the ability of firms to operate energy-intensive machinery. Recent research on African firms reinforces this distinction, showing that energy reliability

and consumption can matter for enterprise performance even where simple access measures produce relatively modest effects (Geginat & Ramalho, 2018).

This distinction raises an important empirical question. Does increasing energy access automatically translate into higher productivity? Conventional development reasoning would suggest that the answer should be affirmative. Energy is an essential input into production, and removing an infrastructure constraint should permit firms and households to increase output. Yet the empirical evidence increasingly suggests that the relationship is more complicated.

Ogundipe et al., (2018), for example, show theoretically that the short-run effects of electricity disruptions on firm productivity may be modest even though the long-run general-equilibrium consequences can be substantially larger. Their argument is important because it suggests that electricity constraints can affect productivity through firm scale, investment and entry rather than only through contemporaneous production losses. Similarly, recent evidence from Malawi identifies an "access-productivity gap", arguing that electricity access alone may not produce large enterprise-level gains when reliability, affordability, finance, technology and business capabilities remain constrained.

The literature therefore points towards an important possibility: energy access may be a necessary but insufficient condition for productivity transformation.

This paper develops that argument by introducing technological advancement as a conditioning factor. The underlying proposition is straightforward. Electricity and clean energy provide productive opportunities, but firms and sectors require complementary technologies, skills, equipment and organisational capabilities to exploit those opportunities. A farmer with electricity but without irrigation equipment, cold storage or processing machinery may receive little productivity benefit from electrification. Similarly, a manufacturing firm connected to the grid may remain constrained if it lacks modern machinery, digital production systems or the capital required to adopt energy-using technologies. Services may respond differently because digitalisation, telecommunications and information-processing technologies can make energy access more immediately productive.

This technological-complementarity perspective is consistent with endogenous growth theory. Romer (1990) conceptualises technological change as an outcome of deliberate investment and emphasises the importance of knowledge and human capital in generating sustained productivity growth. Lucas (1988), similarly, places human-capital accumulation and learning at the centre of development and productivity dynamics. From this perspective, energy infrastructure and technological capability should not necessarily be treated as independent growth determinants. Their interaction may be more important than their isolated effects.

The present study therefore asks a more precise question than the conventional energy-growth literature: Does technological innovation determine whether energy access translates into sectoral productivity in SSA?

The study makes four contributions.

First, it moves away from aggregate economic growth and examines the energy-productivity relationship separately across agriculture, industry and services. This is important because energy intensity, technology use and production structures differ substantially across sectors.

Second, the study distinguishes between electricity access and access to clean fuels and technologies. Treating energy access as a single aggregate concept can obscure important differences in the productive uses of electricity and clean energy.

Third, the study explicitly models technological advancement as a moderator of the energy-productivity relationship. Rather than asking only whether technology directly raises productivity, the paper examines whether technology changes the productivity payoff from energy access.

Fourth, the study investigates distributional heterogeneity and nonlinearities. The average coefficient from a fixed-effects model may conceal substantial differences between low-productivity and high-productivity economies. Likewise, a linear model may miss the possibility that electricity access has little effect below a critical level of network penetration but becomes more productive after a threshold is reached.

These issues are particularly important in SSA because the region is characterised by large differences in productive structure, infrastructure quality, human capital, technological capability and energy systems. The same increase in electricity access may therefore produce very different outcomes in an agrarian economy, an emerging manufacturing economy and a service-oriented economy.

The paper proceeds as follows. Section 2 reviews the theoretical and empirical literature and develops the hypotheses. Section 3 discusses the data and methodology. Section 4 presents the empirical findings. Section 5 discusses the results in relation to the existing literature. Section 6 concludes and develops sector-specific policy implications.

1.2 Statement of the Problem

Energy poverty represents one of the most persistent developmental barriers facing Sub-Saharan Africa (SSA). Despite major international initiatives, such as the United Nations Sustainable Development Goal 7 (SDG 7) and regional power pool integrations, over 580 million people in SSA still lack access to reliable electricity, and upwards of 900 million lack access to clean cooking fuels (IEA, 2022; World Bank, 2024). Traditional economic growth theory posits that infrastructure investments, particularly energy, provide fundamental inputs that enhance factor productivity, expand manufacturing capacity, and accelerate structural transformation (Barro, 1990; Stern, 2011).

However, macro-level aggregate estimations often mask deep structural asymmetries across economic sectors. The energy requirements, technology intensity, and factor proportions of agriculture, industry, and services differ fundamentally. Agriculture in SSA remains largely dominated by rain-fed farming and low-capital techniques, where electrification without modern machinery yields minimal returns (Omoju et al., 2020). Conversely, manufacturing and services rely heavily on uninterruptible power and digital infrastructure to mitigate severe operational bottlenecks (Adenikinju, 2005; Abeberese, 2017).

A crucial, yet insufficiently analyzed, mechanism in the energy-growth nexus is the moderating role of technological innovation. While expanded energy access supplies the raw physical input, technological innovation, such as automated machinery, cold-chain storage, digital platforms, and energy-efficient capital equipment, determines an economy's absorptive capacity to convert energy into Total Factor Productivity (TFP) gains (Romer, 1990; Aghion et al., 2021).

This study addresses four core gaps in the literature:

1. Multidimensional Sectoral Disaggregation: Evaluating how distinct dimensions of energy access (electricity grid access vs. clean fuel access) affect labor productivity across agriculture, industry, and services individually.
2. Technological Moderation Mechanisms: Testing whether technological innovation serves as a complementary mechanism that unlocks latent productivity gains from expanded energy infrastructure.
3. Threshold and Non-Linearities: Identifying whether minimum critical masses of electricity access must be attained before sector-level productivity improvements materialize.
4. Conditional Distributional Heterogeneity**:** Uncovering how energy access effects vary across low-, medium-, and high-productivity SSA economies using panel quantile methods.

2. Literature Review and Theoretical Framework

2.1 Energy access and productivity

The relationship between energy and economic productivity rests on a simple production principle: energy is an input that complements labour, physical capital and technology. Energy shortages therefore constrain production not only because energy itself is unavailable, but also because complementary capital cannot be fully utilised.

This mechanism is particularly relevant in developing economies. A firm may possess machinery but operate below capacity because electricity is unavailable for several hours each day. A farmer may have access to land and labour but lack electricity for irrigation, processing or refrigeration. A service provider may possess digital equipment but remain unable to operate effectively because electricity interruptions disrupt internet connectivity, data processing or commercial transactions. The empirical literature generally supports the existence of an energy-productivity relationship, but the magnitude and consistency of the relationship vary considerably.

The relationship between energy consumption, energy infrastructure, and economic growth has been widely documented (Ozturk, 2010; Ogundipe et al., 2018). Studies focusing on SSA show that energy shortages directly impede industrialization and firm competitiveness (Adenikinju, 2005; Allcott et al., 2016). However, empirical studies disaggregating energy access by economic sector remain sparse and yield conflicting conclusions. For example, Omoju et al. (2020) find that rural electrification has an insignificant direct effect on agricultural productivity in SSA due to the absence of modern agricultural processing equipment.

Nguyen and Su (2021), using evidence from 45 developing countries, find that different dimensions of energy poverty are associated with productivity outcomes, highlighting the possibility of a mutually reinforcing relationship between energy deprivation and productivity. Their contribution is important because it moves beyond the traditional energy-consumption-growth literature and treats energy poverty as a multidimensional development constraint.

Similarly, evidence from 100 developing countries indicates that energy poverty is associated with lower productive efficiency. The negative relationship is particularly relevant because the analysis suggests that the effect is not simply a consequence of differences in national income.

More recent African research reinforces the industrial dimension of this relationship. Ouedraogo and Ouedraogo (2026), examining 33 African countries, report a positive relationship between improved electricity access and industrial performance and argue that energy poverty constitutes an important constraint on industrialisation.

However, evidence from these studies does not imply that energy access automatically produces productivity gains. The relevant distinction is between energy availability and productive utilisation**.**

Energy planning research in SSA increasingly emphasises productive uses of electricity. Productive demand for electricity can substantially affect the economics of electrification because agriculture, industry and commercial activities require different quantities and forms of energy. This distinction motivates the central argument of the present study.

2.2 Sectoral differences in the energy-productivity relationship

Agriculture

Agriculture is one of the sectors in which energy can potentially generate large productivity gains. Electricity can facilitate irrigation, mechanisation, milling, refrigeration, storage and processing. Clean energy technologies can also reduce reliance on inefficient traditional fuels and improve the productivity of agricultural households.

However, the productivity effect depends heavily on complementary capital.

Electricity without irrigation equipment does not irrigate crops. Electricity without refrigeration does not eliminate post-harvest losses. Electricity without processing equipment does not automatically transform agricultural commodities into higher-value products.

Recent evidence from Nigeria illustrates this point. Ojo (2025) finds that multidimensional energy poverty is associated with agricultural productivity among farming households, demonstrating the relevance of energy conditions to agricultural performance. Similarly, recent SSA evidence links energy poverty and environmental constraints to agricultural productivity. This suggests that technological capability should play a particularly important role in agriculture.

Industry

The industrial sector is intrinsically energy intensive. Manufacturing firms use electricity for machinery, processing, lighting, cooling, automation and information systems. Energy unreliability can therefore affect both production and investment decisions.

Recent African evidence supports this relationship. Studies of African industrialisation find that energy poverty impedes industrial development, while new evidence indicates that reducing energy poverty improves industrial performance.

Nevertheless, industrial productivity may require a sufficiently broad energy infrastructure before access produces substantial effects. A small increase in national electrification may not materially improve industrial productivity if electricity remains geographically concentrated in urban areas or if supply is insufficient for industrial loads. This provides a theoretical basis for testing nonlinearities.

Services

Services have a different technological structure. Modern services increasingly depend on electricity, digital devices, telecommunications, data centres, internet connectivity and electronic payment systems. Consequently, electricity access may have a relatively direct productivity effect when combined with digital technology.

At the same time, services are heterogeneous. Retail activities, hospitality, transport, finance, telecommunications and professional services have different energy requirements. This heterogeneity may explain why aggregate service-sector estimates do not necessarily mirror industrial or agricultural results.

Recent research on African businesses shows that digital adoption can increase electricity intensity while simultaneously encouraging product and process innovation. This demonstrates that technological advancement may alter the quantity and productivity of energy use rather than simply substitute for energy.

2.3 Theoretical Framework

This study is built upon an augmented Solow-Swan endogenous growth model incorporating energy inputs (E) and technological absorptive capacity (A) into a sectoral Cobb-Douglas production structure:

$$Yi,j,t = Ai,t\phi Ki,j,t\alpha Li,j,t\beta Ei,t\gamma e\varepsilon i,j,t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where Yi,j,t is output in sector j (Agriculture, Industry, Services) for country i at time t; K is capital stock; L is labor input; and E is multidimensional energy access. Dividing both sides by labor (L) yields sectoral labor productivity (yi,j,t=Yi,j,t/Li,j,t):

$$ln(yi,j,t) = \alpha 0 + \alpha 1 ln(ki,j,t) + \beta 1 ELECi,t + \beta 2 CLEANi,t + \beta 3 TECHi,t + \beta 4 (ELECi,t \times TECHi,t) + \Gamma Xi,t + \mu i + \lambda t + \varepsilon i,t \ldots\ldots\ldots\ldots\ldots 2$$

Here, β4 captures the moderation effect. If β4>0, technological innovation acts as a complementary factor that amplifies the productivity returns of energy access.
The endogenous growth theory highlights technology as the primary driver of long-run productivity (Romer, 1990; Aghion et al., 2021). In developing regions, technological adoption allows firms and farms to optimize energy inputs. Falchetta (2021) note that renewable off-grid energy systems yield major agricultural productivity gains only when coupled with productive-use equipment (PUE) such as solar irrigation pumps and mechanized mills.

Threshold Effects in Infrastructure Development

Network economic theory suggests that infrastructure investments exhibit non-linear threshold effects (Aghion & Howitt, 1997). Prior to reaching a critical density or reliability threshold, individual connections fail to trigger systemic efficiency gains due to frequent outages, voltage fluctuations, and high connection overheads (World Bank, 2013, Blimpo & Cosgrove-Davies, 2019).

3. Data and Econometric Methodology

3.1 Data and Sample

The dataset comprises a dynamic panel of 38 Sub-Saharan African countries observed annually from 2000 to 2022 (N=38,T=23,N×T=874). Primary data were retrieved from the World Bank's *World Development Indicators* (WDI) and *UNCTADstat*.

TABLE 1: VARIABLE DEFINITIONS AND SOURCES

Variable Name	Role	Description / Proxy	Source
AGR_PROD	Dependent Var	Agricultural Value Added per Worker (Constant 2015 USD)	WDI
IND_PROD	Dependent Var	Industrial Value Added per Worker (Constant 2015 USD)	WDI
SER_PROD	Dependent Var	Services Value Added per Worker (Constant 2015 USD)	WDI
ELEC_ACC	Main Explanatory	Access to Electricity (% of total population)	WDI
CLEAN_FUEL	Main Explanatory	Access to Clean Fuels & Tech for Cooking (% pop)	WDI
TECH_INNOV	Moderator	Technological Innovation Index (Composite: High-Tech Imports, Patent Applications, Mobile Subscriptions)	UNCTAD / WDI
CAP_FORM	Control	Gross Fixed Capital Formation (% of GDP)	WDI
HUM_CAP	Control	Human Capital Index (Schooling Years + Health)	Penn World
INST_QUAL	Control	Institutional Quality Index (WGI Composite)	WGI
INFLATION	Control	Consumer Price Index Annual Inflation Rate (%)	WDI

TABLE 2: DESCRIPTIVE STATISTICS (2000–2022)

Variable	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
ln(AGR_PROD)	6.842	0.812	4.910	8.915	0.214	2.450
ln(IND_PROD)	8.915	0.941	6.120	11.230	0.112	2.890
ln(SER_PROD)	8.410	0.732	6.210	10.450	0.305	2.710
ELEC_ACC (%)	38.420	24.810	4.120	98.500	0.680	2.180
CLEAN_FUEL (%)	22.150	21.340	0.800	89.100	1.420	3.950
TECH_INNOV	0.285	0.184	0.012	0.890	1.150	3.620
CAP_FORM (% GDP)	21.450	8.920	4.110	58.200	0.820	3.810
HUM_CAP	1.850	0.420	1.110	2.920	0.340	2.100
INST_QUAL	-0.540	0.620	-1.890	1.120	0.120	2.550
INFLATION (%)	7.850	11.240	-8.500	98.100	4.210	22.40

Source: Authors' Computation, 2026

3.2 Econometric Methodology

1. Baseline Fixed Effects (FE) & Two-Stage Least Squares (2SLS)

To control for unobserved time-invariant country heterogeneity and macro-shocks, the baseline model is specified as:

$$ln(yi,j,t) = \alpha 0 + \beta 1ELECi,t + \beta 2CLEANi,t + \beta 3TECHi,t + \beta 4(ELECi,t \times TECHi,t) + \gamma Xi,t + \mu i + \lambda t + \varepsilon i,t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

2. System Generalized Method of Moments (Sys-GMM)

To address dynamic endogeneity, reverse causality (e.g., higher productivity driving grid investment), and omitted variable bias, we employ the System GMM estimator (Blundell & Bond, 1998):

$$ln(yi,j,t) = \alpha 0 + \delta ln(yi,j,t-1) + \beta 1ELECi,t + \beta 2CLEANi,t + \beta 3TECHi,t + \beta 4(ELECi,t \times TECHi,t) + \gamma Xi,t + \mu i + \lambda t + \varepsilon i,t$$

Instruments are restricted to prevent instrument proliferation, validated via the Hansen test for overidentifying restrictions and the Arellano-Bond AR(2) autocorrelation test.

3. Quadratic Non-Linear Threshold Model

To capture potential non-linear tipping points in energy access, quadratic terms are added:

$$ln(yi,j,t) = \alpha 0 + \beta 1ELECi,t + \beta 2ELECi,t2 + \beta 3TECHi,t + \gamma Xi,t + \mu i + \varepsilon i,t$$

The critical threshold (ELEC∗) is computed as:

ELEC∗=−2β2β1

4. Panel Quantile Regression

To evaluate distributional impacts across productivity tiers (τ∈{0.10,0.25,0.50,0.75,0.90}), we apply Koenker & Bassett's (1978) quantile regression framework:

Qτ(ln(yi,j,t)|Xi,t)=α(τ)+β1(τ)ELECi,t+β2(τ)TECHi,t+β3(τ)(ELECi,t×TECHi,t)+γ(τ)Xi,t

4. Empirical Results and Discussion

TABLE 3: SYSTEM-GMM ESTIMATION RESULTS (BY SECTOR)

	AGRICULTURE (AGR_PROD)		INDUSTRY (IND_PROD)		SERVICES (SER_PROD)	
Variables	(1)	(2)	(3)	(4)	(5)	(6)
ln(Lagged Productivity)	0.712***	0.685***	0.814***	0.792***	0.755***	0.721***
	(0.041)	(0.038)	(0.035)	(0.032)	(0.029)	(0.031)
ELEC_ACC	0.008	-0.005	0.012	-0.018*	0.009	-0.011

	(0.012)	(0.009)	(0.015)	(0.010)	(0.011)	(0.008)
CLEAN_FUEL	0.004	0.002	0.009	0.007	0.038**	0.031**
	(0.008)	(0.007)	(0.011)	(0.010)	(0.016)	(0.014)
TECH_INNOV	0.028*	0.019	0.075***	0.061**	0.052**	0.044**
	(0.015)	(0.014)	(0.022)	(0.020)	(0.021)	(0.019)
ELEC × TECH	,	0.046***	,	0.012	,	0.008
		(0.012)		(0.015)		(0.011)
CLEAN × TECH	,	0.038**	,	0.005	,	0.010
		(0.016)		(0.009)		(0.012)
CAP_FORM	0.014**	0.012**	0.031***	0.029***	0.018**	0.017**
HUM_CAP	0.082**	0.079**	0.115***	0.108***	0.092***	0.088***
INST_QUAL	0.041*	0.038*	0.068**	0.062**	0.051**	0.049**
INFLATION	-0.005**	-0.004**	-0.008***	-0.008***	-0.004*	-0.004*
Observations	798	798	798	798	798	798
Instruments Count	28	31	28	31	28	31
Hansen p-value	0.345	0.281	0.412	0.380	0.488	0.415
AR(1) p-value	0.001	0.001	0.000	0.000	0.001	0.001
AR(2) p-value	0.420	0.395	0.510	0.485	0.362	0.380

Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01.

TABLE 4: NON-LINEAR THRESHOLD MODEL ESTIMATIONS (POLYNOMIAL FIXED EFFECTS)

	AGRICULTURE (AGR_PROD)		INDUSTRY (IND_PROD)		SERVICES (SER_PROD)	
Variables	(1)	(2)	(3)	(4)	(5)	(6)
ELEC_ACC	0.009	-0.012	-0.038**	-0.042**	-0.029*	-0.031**
	(0.011)	(0.010)	(0.016)	(0.015)	(0.015)	(0.014)
ELEC_SQ	0.0001	0.0001	0.00041***	0.00044***	0.00031**	0.00033**
	(0.0001)	(0.0001)	(0.00012)	(0.00011)	(0.00013)	(0.00012)
TECH_INNOV	,	0.031**	,	0.071***	,	0.055**
Controls	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Derived Threshold (ELEC*)	N/A	N/A	46.34%	47.72%	46.77%	46.97%
R-squared	0.412	0.445	0.582	0.612	0.521	0.548

Standard errors in parentheses. * p<0.10, ** p<0.05, *** p<0.01. Calculated turning point average for Industry/Services: ~47.3%.

TABLE 5: PANEL QUANTILE REGRESSION RESULTS (MODERATED MODEL)

Dependent Var / Quantiles	10th (q10)	25th (q25)	50th (q50)	75th (q75)	90th (q90)
PANEL A: AGRICULTURAL PRODUCTIVITY					

ELEC_ACC	-0.004	0.002	0.008	0.012	0.011
ELEC × TECH	0.021*	0.042***	0.058***	0.049***	0.025*
CLEAN × TECH	0.018	0.035**	0.041***	0.032**	0.019
PANEL B: INDUSTRIAL PRODUCTIVITY					
ELEC_ACC	-0.022**	-0.015*	0.005	0.021*	0.034**
ELEC × TECH	0.005	0.009	0.014	0.018	0.012
CLEAN × TECH	0.002	0.004	0.006	0.008	0.005
PANEL C: SERVICE PRODUCTIVITY					
ELEC_ACC	-0.012	-0.008	0.011	0.024**	0.031**
CLEAN_FUEL	0.018*	0.029**	0.038***	0.042***	0.035**
ELEC × TECH	0.004	0.007	0.010	0.012	0.009
----------Controls Included	YES	YES	YES	YES	YES

====Standard errors bootstrapped (1000 repetitions). * p<0.10, ** p<0.05, *** p<0.01.
Source: Authors' Computation, 2026

4.3 Discussion of Findings

1. The Paradox of Unmoderated Electrification
The baseline GMM estimations (Table 3, Columns 1, 3, 5) demonstrate that linear, standalone electricity access (ELEC_ACC) does not exert a statistically significant positive effect on productivity in agriculture, industry, or services. This finding aligns with Omoju et al. (2020) and Blimpo & Cosgrove-Davies (2019), who note that expanding low-capacity, unreliable rural grid lines to low-income communities primarily subsidizes basic household lighting rather than driving productive usage. Without complementary capital tools, electrification alone cannot increase output per worker.

2. Technological Innovation as an Agricultural Catalyst
When technological innovation is introduced as an interaction term (Table 3, Column 2), the interactive coefficients (ELEC × TECH = 0.046, p<0.01; CLEAN × TECH = 0.038, p<0.05) turn positive and highly significant in agriculture. Sub-Saharan agricultural productivity relies heavily on resolving supply-chain bottlenecks, such as post-harvest storage losses, manual irrigation, and inefficient primary processing. When electrification is paired with technological innovation (e.g., solar-powered cold storage, automated drip irrigation, mobile-enabled processing equipment), factor productivity increases substantially (Falchetta, 2021). In contrast, interaction coefficients in industry and services are statistically insignificant, reflecting high existing baseline technological incorporation in urban firms relative to the severe structural deficits in rural agriculture.

3. Threshold Dynamics in Industry and Services
The quadratic estimations in Table 4 show a robust U-shaped non-linear relationship in the industrial and service sectors. The linear electricity coefficients are negative, whereas the squared coefficients (ELEC_SQ) are positive and significant (p<0.01 for industry; p<0.05 for services).
Differentiating the quadratic equation yields a critical access threshold:

$$ELEC* = \frac{2 \times 0.00044}{0.042} \approx 47.72\% \ (Industry)$$

$$ELEC* = \frac{2 \times 0.00033}{0.031} \approx 46.97\% \ (Services)$$

Across both sectors, the tipping point averages b. Below this threshold, fragmented power grids, frequent outages, and heavy reliance on expensive diesel generators create severe cost inefficiencies (Adenikinju, 2005; World Bank, 2024). Once electricity access exceeds ~47%, economies of scale, network externalities, and reliable grid integration emerge, generating net positive productivity gains across industrial and commercial service ecosystems.

4. Distributional Heterogeneity Across Quantiles
Panel quantile regressions (Table 5) show distinct distributional patterns:

- Agriculture: The technological interaction effect (ELEC × TECH) peaks in the middle quantiles (25th to 50th quantiles, $\beta=0.058, p<0.01$). Low-productivity farms (10th quantile) face severe land tenure and capital credit constraints that limit technological adoption, whereas top-tier farms (90th quantile) have already integrated modern technologies.
- Industry & Services: Direct electricity access becomes positive and statistically significant only at the upper quantiles (75th and 90th quantiles). High-productivity economies possess the structural maturity, manufacturing bases, and financial depth required to fully leverage expanded grid infrastructure.

5. Conclusion and Policy Recommendations

5.1 Conclusion

This study provides empirical evidence on the relationship between multidimensional energy access, technological innovation, and sectoral productivity across 38 Sub-Saharan African economies. The findings demonstrate that expanding energy access alone is insufficient to guarantee broad-based productivity growth. Technological innovation serves as a key catalytic moderator that unlocks productivity gains in agriculture. Moreover, industrial and service sector productivity gains depend on crossing a critical infrastructure threshold of approximately 47% electricity access.

5.2 Policy Recommendations

1. Target Productive-Use Electrification (PUE) in Agriculture: National electrification programs should move beyond grid expansion metrics to prioritize the deployment of Productive-Use Equipment (PUE), including solar irrigation systems, electric processing mills, and cold-chain storage facilities.
2. Prioritize Industrial Clusters to Reach Threshold Scale: Governments should concentrate energy infrastructure investments into Special Economic Zones (SEZs), industrial parks, and urban commercial hubs to cross the critical 47% threshold necessary for network economies of scale[cite: 1].
3. Promote Clean Cooking Systems for Commercial Services: Given the positive impact of clean fuel access on service sector productivity, targeted subsidies and credit support should be directed toward modern cooking technologies in commercial food service and informal urban micro-enterprises[cite: 1].
4. Synchronize Energy and Technology Policies: Regional bodies (e.g., African Union, ECOWAS, EAC) and national ministries must align energy master plans with national science, technology, and innovation (STI) frameworks to ensure firms possess the absorptive capacity to fully utilize expanded energy infrastructure[cite: 1].

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THE ROLE OF THE DEPARTMENT OF CULTURE AND TOURISM IN INCREASING TOURIST VISITS TO THE SAMBALIUNG PALACE IN BERAU REGENCY

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ABSTRACT
This research describes how to increase tourist visits in Berau regency. It was conducted with a qualitative descriptive approach using structured interviews as a data collection technique for six key informants from the head of the department while the informants were the Camat, Keraton Management, Youth Leaders, and visitors. This research also focuses on the Berau Regency Regional Regulation No. 13 of 2008 concerning the main tasks and functions of Berau Regency Culture and Tourism Office in increasing the number of tourist visits to the Sambaliung Palace through programs and activities. The results showed that the role of the cultural and tourism department in increasing tourist visits to the Sambaliung Palace, Berau Regency was recovered. However, budget and the way government used to improved and stabilized the image of tourism are the problems in increasing visits to the Sambaliung Palace. In this case the cultural tourism of the Sambaliung Palace has apparently been carried out through social media, and suggestions for contributions. Hopefully, in building the image of tourism, the promotions will be carried out well so that the benefits will be more enjoyed by the community and local government.
Keywords: tourist, agency, cultural tourism.

DIGITAL TRANSFORMATION AND WOMEN'S ENTREPRENEURIAL DEVELOPMENT IN THE WESTERN BALKANS: EVIDENCE FROM SECONDARY DATA

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Abstract
Digital transformation has become a key driver for economic and entrepreneurial development, creating new chances for women to engage in business and access markets, information, finance, and digital services. In the Western Balkans, however, variations in digital infrastructure, economic development, and access to opportunities still affect how much women can profit from digitalisation. The study examined the relationship between digital transformation and women's entrepreneurial development in six Western Balkan economies: Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia. The analysis is based on secondary data only, taken from worldwide standard sources such as the World Bank and the World Telecommunication Union for the period 2010–2024. Digital transformation is measured by selected measures of internet use, digital connection, and access to digital technologies; women's entrepreneurial development is measured by available indicators of women's economic and entrepreneurial engagement. The empirical analysis adopts descriptive statistics, correlation analysis, and panel regression to explore the relationship between digital transformation and women's entrepreneurial development. The findings are expected to show a positive correlation between higher digital connectivity and women's engagement in entrepreneurial activities and point to disparities among the Western Balkan economies. This study adds to the field by offering comparative findings from an area where digital transformation and inclusive entrepreneurship are still major policy priorities. The findings may give useful implications for policymakers aiming at improving digital inclusion, women's entrepreneurship and sustainable economic development in the Western Balkans.
Keywords: digital transformation, women's entrepreneurship, digitalization, digital inclusion, Western Balkans, entrepreneurial development.

THE RELATIONSHIP BETWEEN REMITTANCES AND INSURANCE IN NIGERIA

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Abstract
The importance of remittances to financial development and economic growth has been largely addressed in the literature. However, the relevance of remittances to insurance has not attracted adequate attention, particularly in Nigeria. Therefore, this study examined the impact of remittances on insurance in Nigeria during the period from 1991 to 2024. The study employed the Autoregressive Distributed Lag (ARDL) for the estimation of the results. The results obtained from the ARDL estimations show that remittances enhanced insurance development in the long-run. Remittances produce an insignificant impact on insurance in the short-run. In relation to our findings, there is a need for policymakers to work in collaboration with commercial banks and remittance service providers to establish remittance-linked insurance schemes that can encourage voluntary purchase of insurance products by households.
Keywords: Remittances, insurance, ARDL, GDP per capita growth, Nigeria, inflation,

APPROACH TO THE LABOR POVERTY IN THE STATE OF TABASCO, MEXICO

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Abstract
There are numerous studies and debates regarding poverty and the average income families have available to purchase a basic food basket. The objective of this study is to analyze trends in labor poverty and real per capita income in the state of Tabasco, based on statistical data published quarterly by INEGI and methodologies established by the General Law on Social Development (LGDS). The research relied on secondary sources from public agencies. The findings indicate that per capita labor income rose from 2,312.99 pesos in the first quarter of 2016 to 2,608.48 pesos in the first quarter of 2026. Additionally, a decline in average labor income among employed men and women was observed between the first quarter of 2025 and the first quarter of 2026 specifically 0.7% and 1.3%, respectively along with an identification of the economic sectors most affected. The study concludes that this information is vital for formulating public policy and strengthening family wage income.
Keywords: Food basket, Income, Labor poverty, Per capita income

GAME THEORY AND THE OLIGOPOLY OF RETAIL STORES WAL-MART, CHEDRAUI, AND SORIANA IN VILLAHERMOSA, TABASCO

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Abstract
This study analyzes the strategies employed by oligopolistic retail chains—such as Wal-Mart, Chedraui, and Soriana operating in the city of Villahermosa, Tabasco. An oligopoly is a market structure characterized by the presence of many sellers of varying sizes, yet dominated by a few major players that capture the bulk of the sector, contrasting with smaller local stores like Súper Sánchez, Abarrotes Monterrey, and Abarrotes La Guadalupana. The objective is to examine the performance and strategies specifically game theory used by small grocery stores when competing against these oligopolies, and to determine whether such strategies are crucial for market survival. A mixed-methods approach (combining quantitative and qualitative analysis) was used to explore the application of game theory as a decision-making tool for small grocery stores facing oligopolistic competition; bibliographic sources, primarily specialized texts on the subject, were also consulted. The study concluded that small grocery stores do not utilize game theory in their business decision-making processes; conversely, it was observed that the dominant retail chains employ competitive strategies that adapt to changing market conditions.
Keywords: Game theory, Oligopoly, Retail stores, Cooperative games

ECONOMIC STUDY OF THE PHARMACEUTICAL MARKET IN VILLAHERMOSA TABASCO, MÉXICO

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Abstract
In Tabasco and specifically in Villahermosa there is a high concentration of pharmacies located in close proximity to one another. This research examines the behavior and current situation of retail pharmacies, as well as the strategies they employ to compete in the sector. The landscape includes chains such as Guadalajara, del Ahorro, Similares, Unión, and Yza, along with the specialty pharmacy *Farmacia de Especialidad Villahermosa* and in-store pharmacies at major retailers like Chedraui, Soriana, and Walmart. The study aims to identify the market strategies used by these clustered pharmacies and to understand the impact of this proximity on customer numbers and profit margins. It is an exploratory and descriptive study based on existing knowledge and data from Economic Censuses. The work reviews theories regarding oligopolies, game theory, and inter-firm cooperation, while also analyzing the Herfindahl-Hirschman Index (HHI) to assess market concentration. The findings reveal that for pharmacies located near one another, competition follows an oligopolistic pattern consistent with game theory characterized by specific strategies such as marketing initiatives and the provision of unique services not offered by competitors.
Keywords: Game Theory, Market, Competitive Strategies, Oligopoly.

THE INFORMALITY PREMIUM: HOW EDUCATION SHAPES THE WILLINGNESS TO WORK INFORMALLY

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Abstract

This paper examines whether education affects individuals' willingness to engage in informal employment and to what degree, if at all, this relationship operates through economic and normative channels. Informal employment remains widespread across developing and transition economies, yet most existing work focuses on whether individuals actually participate in the informal sector rather than on how willing they are to do so. Using original survey data from 400 respondents in Albania, this study introduces the informality premium, defined as the additional monthly compensation an individual would require to accept an informal job, as a novel measure of willingness to work informally. The results show that education is positively and significantly associated with the size of the premium, even after controlling for income, age, gender, and location, with the effect concentrated among those holding postgraduate qualifications. By contrast, education does not independently predict the outright refusal of informal employment once individual characteristics are accounted for, and awareness of the specific risks of informal work neither varies with education nor explains the premium. These findings suggest that the relationship between education and informality concerns not only whether individuals work informally, but also the terms on which they are prepared to do so, offering a more granular view of how education shapes engagement with the informal economy.

Keywords: informal employment, informality premium, education, Albania, tax morale, willingness, human capital, shadow economy

CROSS-BORDER DIGITAL PAYMENTS AND MONETARY SOVEREIGNTY: THE EMERGING ECONOMIC ARCHITECTURE OF BRICS

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Abstract

The expansion of the BRICS bloc and the accelerating global shift toward central bank digital currencies (CBDCs) and blockchain-based settlement systems are reshaping the legal and economic architecture of cross-border finance. Against a backdrop of escalating geopolitical fragmentation and sanctions-driven financial bifurcation, BRICS states have intensified efforts to reduce dependency on dollar-denominated correspondent banking and legacy SWIFT infrastructure. This paper examines how cross-border digital payment initiatives whether multilateral platforms, bilateral local-currency arrangements, or prospective CBDC bridges interact with the principle of monetary sovereignty under contemporary international economic law. Digital payment integration promises to lower transaction costs, accelerate settlement speed, and enhance macroeconomic autonomy for emerging economies, yet it simultaneously risks eroding traditional monetary sovereignty by subjecting domestic payment rails to extraterritorial technical standards, surveillance protocols, and currency substitution pressures. U.S. jurisprudence illustrates the stakes; federal courts have long recognized that foreign central banks possess sovereign immunity under the Foreign Sovereign Immunities Act, insulating them from domestic suit and underscoring the territorial exclusivity that nations assert over monetary authority. Conversely, domestic courts have shown willingness to regulate virtual-currency transmissions as money-services businesses, signaling that national regulators treat digital payment infrastructure as subject to local licensure and oversight. Methodologically, the study combines doctrinal analysis of international monetary law (IMF Articles of Agreement, bilateral swap agreements, and FATF standards) with a comparative functional assessment of existing digital payment experiments across BRICS jurisdictions. It evaluates the legal vacuum surrounding CBDC interoperability, the compatibility of digital settlement networks with currency sovereignty under Article VIII of the IMF Articles, and the implications of payment-system fragmentation for global financial stability governance.

Keywords: BRICS, cross-border digital payments, monetary sovereignty, CBDC [Central Bank Digital Currencies], de-dollarization, international monetary law, payment-system governance.

ASMA BUDAMA ATIĞI BİYOKÖMÜRÜ İLE ZENGİNLEŞTİRİLMİŞ HİDROJELLERİN DOMATES (SOLANUM LYCOPERSİCUM L.) BÜYÜME PERFORMANSI VE KLOROFİL İÇERİĞİNE ETKİSİ

EFFECT OF HYDROGELS ENRICHED WITH BIOCAR FROM VINE PRUNING WASTE ON TOMATO (SOLANUM LYCOPERSİCUM L.) GROWTH PERFORMANCE AND CHLOROPHYLL CONTENT

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ÖZET
Kuraklık, esas olarak sıcaklık dalgalanmaları ve düzensiz yağışlar gibi olumsuz süreçlerden kaynaklanan, hücre metabolizmasını bozarak bitki büyümesinin azalmasına, ürün verim kaybına ve toprak bozulmasına yol açan önemli bir etkendir. Hidrojeller ise bu sorunlara kısmen de olsa çözüm üretebilme potansiyeli olan malzemeler olarak görülmektedir. Üç boyutlu polimerik ağ yapısına sahip bu malzemeler yüksek su tutmaları, çevre dostu olmaları, doğada belirli süreler sonunda bozunabilmeleri sebebi ile tercih sebebi olmaktadırlar. Ayrıca bu polimerik ağ yapıları içerisine entegre edilebilen farklı malzemeler ile su tutma ve çevresel dayanımının arttırılabilmesi de önemli özellikleri arasında sayılmaktadır. Bu çalışmada çevresel sürdürülebilirliği ve malzeme döngüsünü sağlayabilmek için bağ budama atıklarından elde edilen biyokömürler PVA/SA polimerik ağ yapısına entegre edilmiş ve domates bitkisinin büyüme parametrelerine etkisi değerlendirilmiştir. Aynı büyüme evresindeki domates fideleri üç faklı oranda (%1,25-%2,5-%3,75 a/a) torf ve biyokömür katkılı hidrojelleri içeren saksılara ekilmiş, 14 günde bir sulanmış ve dört hafta boyunca büyütülmüştür. İlk ve son hafta bitki boyları ve dört hafta boyunca haftada bir fidelerin klorofil içerikleri ölçülmüştür. Bitki boyundaki ve klorofil içeriklerindeki değişimler belirlenmiştir. Bitki boyundaki artış hidrojel/torf oranı arttıkça azalmasına rağmen son hafta klorofil ölçümlerinde özellikle %3,75 hidrojel/torf oranında kontrol grubuna göre klorofil içeriğinin arttığı, aynı hidrojel/torf oranında ise minimum boy oranı belirlenmiştir. Sonuç olarak, kuraklıkla mücadele kapsamında uygulanan biyokömür katkılı hidrojellerin domates bitkilerinin vejetatif büyüme parametreleri üzerinde farklı etkiler gösterdiği ancak potansiyel malzemeler olma eğiliminde oldukları belirlenmiştir.
Anahtar Kelimeler: Bitki boyu, Biyokömür, Domates, Hidrojel, Kuraklık

ABSTRACT
Drought, primarily caused by adverse processes such as temperature fluctuations and irregular rainfall, is a significant factor disrupting cellular metabolism, leading to reduced plant growth, crop yield loss, and soil degradation. Hydrogels are considered materials with the potential to partially address these problems. These materials, with their three-dimensional polymeric network structure, are preferred due to their high water retention capacity, environmental friendliness, and biodegradability in nature after a certain period. Furthermore, the ability to integrate different materials into these polymeric network structures to increase water retention and environmental resistance is also among their important characteristics. In this study, to ensure environmental sustainability and material recycling, biochars obtained from vine pruning waste were integrated into a PVA/SA polymeric network structure, and their effect on the growth parameters of tomato plants was evaluated. Tomato seedlings at the same growth stage were planted in pots containing hydrogels with three different ratios (1.25%-2.5%-3.75% w/w) of peat and biochar, watered every 14 days, and grown for four weeks. Plant heights were measured in the first and last weeks, and chlorophyll content of seedlings was measured weekly for four weeks. Changes in plant height and chlorophyll content were determined. Although the increase in plant height decreased as the hydrogel/peat ratio increased, chlorophyll measurements in the last week showed an increase in chlorophyll content compared to the control group, especially at a hydrogel/peat ratio of 3.75%, while

at the same hydrogel/peat ratio, the minimum height ratio was determined. In conclusion, it was determined that biochar-added hydrogels applied within the scope of drought control showed different effects on the vegetative growth parameters of tomato plants, but they tend to be potential materials.
Keywords: Biochar, Drouhgt, Hydrogel, Plant height, Tomato

GİRİŞ

Kuraklık, tarımsal üretimde verim kayıplarına yol açan en önemli çevresel stres faktörlerinden biridir ve bitkilerin büyüme, gelişme ve fotosentez süreçlerini olumsuz etkiler. Domates (*Solanum lycopersicum*) gibi ekonomik öneme sahip bitkilerde kuraklık stresi, klorofil içeriğinde azalmaya ve bitki boyunda kısalmaya neden olarak ürün kalitesini ve miktarını düşürür. Bu bağlamda, kuraklık koşullarında bitkilerin su tutma kapasitesini artırmak, stres etkilerini azaltmak, tarımsal sürdürülebilirliği ve gıda güvenliğini artırmak için yenilikçi su tasarrufu teknolojilerinin geliştirilmesini ve uygulanması bir zorunluluk haline gelmiştir (Agbna ve Zaidi, 2026). Su kıtlığı, dünya çapında bitki büyümesini ve üretimini sınırlayan başlıca zorluklardan biridir ve iklim değişikliği küresel gıda güvenliğine ciddi bir tehdit oluşturmaktadır. Kuraklık, bitki gelişimini durduran, ürün gelişimini, sağlığını ve verimini olumsuz etkileyen güçlü bir abiyotik stres faktörüdür. İklim değişikliğinin mevcut durumu göz önüne alındığında, su kıtlığı dönemlerinin süresinin ve sıklığının önümüzdeki yıllarda artacağı öngörülmektedir (Bakry vd., 2026; Chen vd., 2025).

Bitki büyümesini ve üretimini önemli ölçüde düşüren, fotosentez ve klorofil biyosentezini, besin alımı ve metabolizmasını olumsuz etkileyen su kıtlığına karşı, bitki direncini artırmak ve su kullanım verimliliğini yükseltmek için yenilikçi yaklaşımlar araştırılmaktadır. Son yıllarda, biyokömür katkılı hidrojeller, toprak su tutma kapasitesini artırmak ve bitkilerin su stresine karşı dayanıklılığını güçlendirmek amacıyla tarımsal uygulamalarda dikkat çekici bir potansiyel göstermektedir. Biyokömür, özellikle tarımsal atıkların (örneğin asma budama atıkları) piroliz yoluyla dönüştürülmesiyle elde edilen karbon zengini bir malzeme olup, toprak yapısını iyileştirme ve su tutma kapasitesini artırma özellikleriyle bilinmektedir. Hidrojeller ise yüksek su tutma kapasiteleri sayesinde bitkilerin su stresine karşı korunmasında etkin bir rol oynayan ve kurak dönemlerde bitki gelişimini teşvik etme potansiyeli ile ilgi çekmektedir. Özellikle, toksik olmayan hidrojel malzemeleri; yüksek emici, uygun maliyetli, dayanıklı, kararlı, suda şiştikten sonra yavaş salınım yapabilen ve çevre dostu biyolojik olarak parçalanabilirlikleri ile öne çıkmaktadırlar (El Idrissi vd. 2024). Üç boyutlu çapraz bağlı polimer ağları içeren bu malzemeler, genellikle kendi ağırlıklarının 100 ila 1500 katı kadar büyük miktarda suyu emme ve tutma ve toprak neminin azalmasına yanıt olarak bitki köklerine kademeli olarak salma konusunda benzersiz bir yeteneğe sahiptir (Agbana ve Zaidi, 2026). Literatür çalışmaları, hidrojellerin özellikle kuru ve yarı kurak bölgelerde toprağın fiziksel (gözeneklilik, yoğunluk, su tutma kapasitesi, toprak geçirgenliği ve infiltrasyon hızı), kimyasal ve biyolojik özelliklerini iyileştirebildiğini (Albalasmeh vd., 2022), kök büyümesini, tohum çimlenmesini ve fidelerin ortaya çıkma hızını artırdığını ve toprak erozyonunu azalttığını göstermektedir (Herawati vd., 2021).

Domates (*Solanum lycopersicum* L.), dünya çapında yaygın olarak yetiştirilmektedir ve mineral, likopen ve C vitamini içeriği nedeniyle tüketiciler tarafından oldukça tercih edilen, lezzeti ve besin değeri yüksek bir sebzedir (Errahali vd., 2025). Birleşmiş Milletler Gıda ve Tarım Örgütü'nün (FAO) 2020 verilerine göre, küresel yıllık üretim 183 milyon tona ulaşmıştır (Chen vd., 2025). Yaşam döngüsü boyunca yüksek su ihtiyacı, domatesin kuraklık stresine karşı oldukça savunmasız bir ürün olmasına sebep olmaktadır (Machado vd., 2025). Çeşitli bitki türlerinde çoklu stres tepkisi ve stres hafızası oluşturabilmesine rağmen, domates bitkilerinin tekrarlanan kuraklık stresine verdiği tepkilerle ilgili kritik bilgi boşluklarının olduğu bilinmektedir (Chen et al 2025). Önceki çalışmalar, domates bitkilerinin kuraklığa duyarlı olduğunu ve özellikle çiçeklenme ve meyve gelişimi sırasında vejetatif büyüme ve üreme için yeterli suya ihtiyaç duyduğunu göstermektedir (Khapte vd. 2019). Ayrıca, domates bitkileri stoma düzenlemesi, fotosentetik reaksiyonlar, ozmolit birikimi ve antioksidan savunma dahil olmak üzere çeşitli mekanizmalar yoluyla su stresine yanıt verdiği de bilinmektedir (Khapte vd. 2019). Bu nedenle, özellikle kurak bölgelerde, toprak su tutma kapasitesini ve bitkinin kuraklığa karşı direncini artırmak, ürün verimliliği için çok önemlidir (Errahali vd., 2025).

Asma budama atıklarından elde edilen biyokömür katkılı hidrojellerin kullanımı, hem sürdürülebilir atık yönetimi hem de kuraklık stresinin olumsuz etkilerinin azaltılması açısından çiftçilere yeni olanaklar sunmaktadır. Bu kompozit malzemelerin, domates bitkisinin klorofil içeriği ve bitki boyu gibi büyüme parametreleri üzerindeki olumlu etkileri, kuraklık koşullarında bitki performansının iyileştirilmesine

katkı sağlayabilir. Bu çalışma, asma budama atıklarından üretilen biyokömür katkılı hidrojellerin kuraklık stresi altındaki domates bitkilerinde klorofil ve bitki boyu üzerindeki etkilerini inceleyerek, sürdürülebilir tarım uygulamalarına katkıda bulunmayı amaçlamaktadır. Literatürde, biyokömür ve hidrojel uygulamalarının bitki su tutma kapasitesi ve stres toleransını artırmadaki olumlu etkileri üzerine artan sayıda çalışma bulunmaktadır. Ancak, asma budama atıklarından elde edilen biyokömür katkılı hidrojellerin domates bitkisi üzerindeki spesifik etkilerine dair çalışmalar sınırlıdır ve bu alandaki bilgi açığını kapatmak için daha fazla araştırmaya ihtiyaç vardır. Kuraklıkla mücadelede biyokömür katkılı hidrojellerin potansiyelinin araştırılması, hem çevresel sürdürülebilirlik hem de tarımsal verimlilik açısından önemli bir bilimsel katkı sağlayacaktır.

MATERYAL-METOD

Biyokömür üretimi

Bu çalışmada kullanılan asma (*Vitis vinifera* L.) budama artıkları bağlardan toplanmış ve sabit tartıma getirmek için 105 °C'de 48 saat etüvde kurutulmuştur. Kurutulan bu hammadde, biyokömür elde etmek için azot gazı akışı altında 500 °C'de 4 saat boyunca bir piroliz reaktörü (UnitermLab) kullanılarak piroliz edilmiştir. Elde edilen ham biyokömür malzemeleri öğütülmüş ve 0,2 mm elekten geçirilerek hidrojel sentezinde kullanmak üzere saklanmıştır.

Hidrojel sentezi

Çalışmada kullanılmak üzere, sodyum aljinat (SA) ve polivinil alkol (PVA) polimerlerinin çözeltisi kullanılarak fiziksel çapraz bağlama yoluyla polimerik kompozit hidrojel boncukları sentezlenmiştir. Kısaca, hidrojel boncukların üretimiyle ilgili olarak, %3 (a/h) PVA ve %2 (a/h) sodyum aljinat polimerleri, homojen bir çözelti elde etmek için 25 °C'de 2 saat boyunca manyetik karıştırıcıda karıştırılmıştır. Hazırlanan PVA/SA çözeltisine %0,2 biyokömür ilave edilerek homojen olana kadar karıştırılmıştır. Daha sonra çözelti, %5 (a/h) $CaCl_2$ çözeltisine damla damla eklenmiş ve manyetik karıştırıcıda (100 rpm) gece boyunca sürekli olarak karıştırılmıştır. Hidrojel boncukları $CaCl_2$ çözeltisinden alınarak birkaç kez deiyonize su ile yıkanmıştır.

Üretilen Biyokömür ve Hidrojellerin Karakterizasyonu

Üretilen biyokömürün ve biyokömür katkılı hidrojellerin yüzey morfolojilerini belirlemek için taramalı elektron mikroskobu (SEM; Quanta 650 FEG, ABD) yapılmıştır.

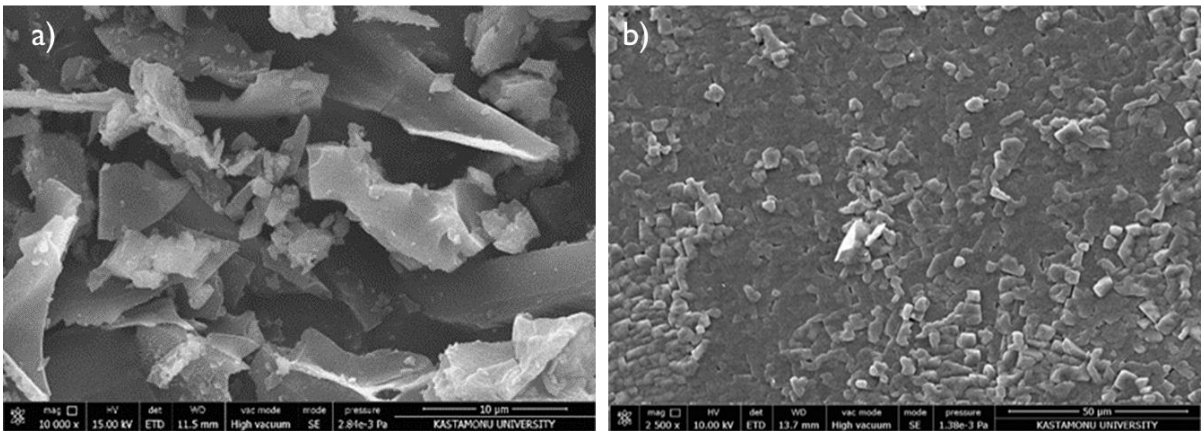
Bitki Denemeleri

Her saksıya 400 g torf ve üretilen hidrojellerden farklı miktarlarda (%1,25-%2,5-%3,75 a/a) eklenerek eşit boydaki domates fideleri ekilmiştir. Can suyunun verilmesinin ardından bitki boyları ölçülmüş, 14 gün ara ile iki sulama gerçekleştirilmiş ve bitkiler 30 gün boyunca büyütülmüştür. Her saksıdan haftalık klorofil ölçümleri Konica-Minolta Klorofil metre ile gerçekleştirilmiştir. İkinci sulamanın ardından son bitki boyları da ölçülmüştür.

BULGULAR

Biyokömür ve Hidrojel Karakterizasyonu

SEM görüntüsü, asma budama atıklarından elde edilen biyokömürün heterojen ve düzensiz bir morfolojik yapıya sahip olduğunu göstermiştir (Şekil 1a). Biyokömürün parçalı yapılar, pürüzlü yüzeyler, çatlaklar ve belirgin boşluklar içerdiği belirlenmiştir. Bu morfolojik özellikler, piroliz işlemi sırasında heterojen ve gözenekli bir yapının oluştuğunu göstermektedir. Gözlenen boşluklar ve yüzey düzensizlikleri, su ve çevresindeki hidrojel matrisi ile etkileşime girebilecek ilave bölgeler sağlayabilir. Bu nedenle, biyokömürün sahip olduğu yüzey özelliklerinin, hidrojel sistemi içerisinde güçlendirici ve su ile etkileşen bir bileşen olarak işlev görmesine katkı sağlayabileceği düşünülmektedir. Biyokömür katkılı hidrojelin SEM görüntüsü, hidrojel matrisi üzerinde heterojen bir yüzey morfolojisi ve düzensiz dağılım gösteren partiküler yapılar ortaya koymuştur (Şekil 1b).

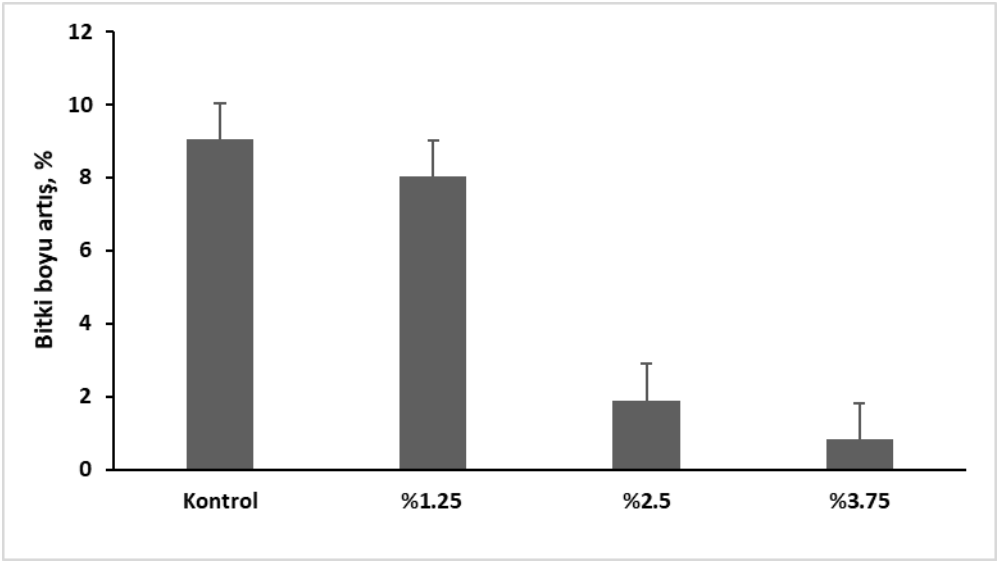


Şekil 1. a) Asma budama atığından elde edilen biyokömürün ve b) biyokömür içeren hidrojellerin SEM görüntüleri

Hidrojel yüzeyinde farklı boyut ve şekillerde partikül benzeri oluşumların yanı sıra, yer yer kümelenmiş yapılar gözlenmiştir. Bu yapıların, biyokömür partiküllerinin hidrojel matrisi içerisinde dağılması ve hidrojel bileşenleriyle etkileşimi sonucunda oluştuğu düşünülmektedir. Önceki SEM görüntüsünde gözlenen asma biyokömürünün düzensiz ve parçalı morfolojisi ile birlikte değerlendirildiğinde, biyokömürün hidrojel matrisi içerisinde belirgin morfolojik izler oluşturduğu görülmektedir. Biyokömür partiküllerinin hidrojel yapı içerisinde bulunması, hidrojel matrisi ile biyokömür arasında fiziksel etkileşimlerin meydana geldiğini ve biyokömürün hidrojel yapısına başarılı bir şekilde dahil edildiğini düşündürmektedir.

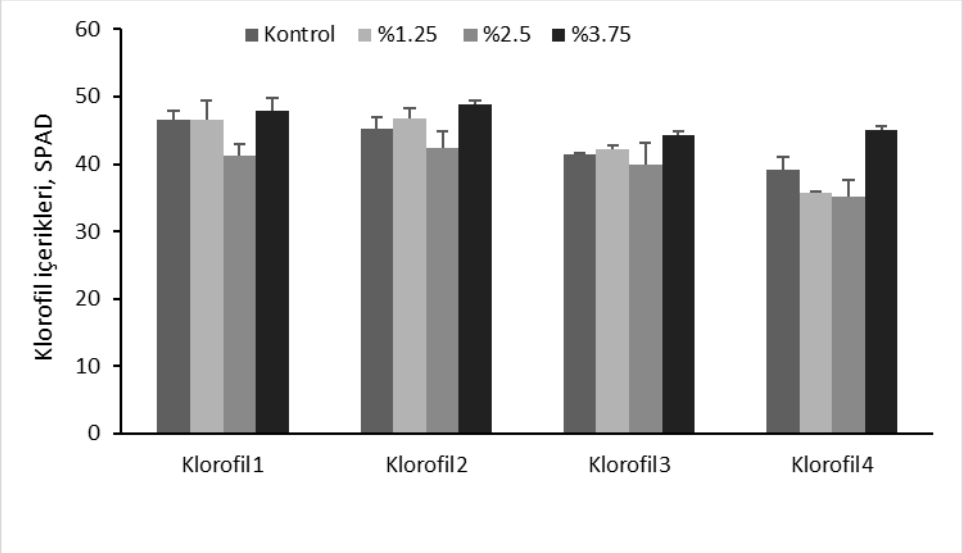
Bitki Boyu ve Klorofil İçeriği

Şekil 2, farklı oranlarda hidrojel uygulamasının bitki boyundaki artış üzerindeki etkisini göstermektedir. Kontrol grubunda bitki boyu artışı %9,038 olarak belirlenirken, %1,25 hidrojel uygulamasında bu değer %8,033'e düşmüştür. Hidrojel uygulama oranının %2,5'e yükseltilmesiyle bitki boyundaki artış %1,896'ya gerilemiş, en yüksek hidrojel uygulama oranı olan %3,75'te ise yalnızca %0,814 olarak kaydedilmiştir. Buna göre, hidrojel uygulama oranındaki artışın bitki boyu artışını olumsuz yönde etkilediği ve özellikle %2,5 ve %3,75 uygulama oranlarında büyüme artışının belirgin şekilde sınırlandığı görülmektedir. Kontrol grubuna kıyasla bitki boyu artışındaki azalma, %1,25, %2,5 ve %3,75 hidrojel uygulamalarında sırasıyla yaklaşık %11, %79 ve %91 düzeyindedir. Bu sonuçlar, hidrojel uygulamasının bitki gelişimi üzerindeki etkisinin uygulama oranına bağlı olduğunu ve yüksek hidrojel oranlarının bitki boyu gelişimi açısından daha düşük performansla ilişkili olabileceğini göstermektedir.



Şekil 2. Farklı hidrojel uygulama oranlarına bağlı olarak domates bitki boyundaki artışın (%) değişimi

Hidrojelin etkisi, polimerin tipi, uygulama miktarı, toprak/substrat özellikleri, bitki türü ve özellikle su rejimine bağlı olarak değişebilmektedir. Örneğin El Idrissi vd. (2023), domateste hidrojel uygulamasının su kısıtı altında bitki boyu ve diğer büyüme parametrelerini etkilediğini ve etkinin hidrojel düzeyine bağlı olduğunu bildirmiştir. %3,75 uygulamasında boy artışının çok düşük olması**,** yüksek hidrojel miktarının kök bölgesindeki fiziksel koşulları değiştirmiş olabileceğini düşündürüyor. Hidrojel parçacıkları suyu tutarak yararlı olabilirken, aşırı miktarlarda kullanıldığında kök bölgesindeki hava-su dengesini, gözenek dağılımını veya köklerin suya erişimini değiştirme ihtimali de bulunmaktadır. Dolayısı ile yüksek hidrojel oranlarının bitki boyu gelişimini sınırlamış olabileceğini düşündürmektedir. Şekil 3, farklı hidrojel uygulama oranlarının dört haftalık ölçüm periyodu boyunca bitkilerin klorofil içeriği (SPAD) üzerindeki etkisini göstermektedir. İlk hafta ölçümlerinde kontrol ve %1,25 hidrojel uygulamalarında klorofil içerikleri yaklaşık 46 SPAD düzeyinde bulunurken, %2,5 uygulamasında daha düşük bir değer (yaklaşık 41 SPAD) belirlenmiştir. Buna karşılık, %3,75 hidrojel uygulaması ilk haftada yaklaşık 48 SPAD ile en yüksek klorofil içeriğini göstermiştir. İkinci haftada genel eğilim büyük ölçüde korunmuş; %3,75 hidrojel uygulamasında klorofil içeriği yaklaşık 48,8 SPAD ile en yüksek değere ulaşırken, %2,5 uygulaması yaklaşık 42,37 SPAD ile en düşük değerde kalmıştır. Üçüncü haftada tüm uygulamalarda klorofil içeriğinde bir miktar azalma gözlenmiş olmakla birlikte, %3,75 hidrojel uygulaması yaklaşık 44,3 SPAD ile diğer uygulamaların üzerinde değer göstermiştir. Dördüncü haftada ise uygulamalar arasındaki farklılık daha belirgin hale gelmiştir. Kontrol grubunda klorofil içeriği yaklaşık 39 SPAD'a gerilerken, %1,25 ve %2,5 hidrojel uygulamalarında değerler yaklaşık 35-36 SPAD düzeyine düşmüştür. Buna karşılık, %3,75 hidrojel uygulamasında klorofil içeriği yaklaşık 45 SPAD ile diğer gruplardan daha yüksek seviyede korunmuştur. Bu durum, yüksek hidrojel oranının bitki boyunu artırmamış olmasına rağmen klorofil içeriğinin korunmasına katkı sağlayabileceğini düşündürmektedir. Örneğin, Al-Gahtany vd. (2024), süper emici hidrojel uygulamasının kuraklık koşullarında ayçiçeğinde büyüme ve klorofil içeriği dahil çeşitli biyokimyasal özellikleri olumlu etkileyebildiğini bildirmiştir. Benzer şekilde, El Idrissi et al. (2023) hidrojel uygulamalarının su kısıtı altında domateste bitki boyu ve klorofil içeriği gibi parametreleri etkilediğini göstermiştir. Frioni et al. (2025) tarafından yapılan çalışmada asma bitkilerine kök bölgesinden süper emici hidrojel uygulanmış ve su kısıtı altında hidrojel uygulamasının toprak su durumunu iyileştirdiği, su potansiyelindeki düşüşü geciktirdiği ve bitkilerin fizyolojik performansını korumaya yardımcı olduğu gösterilmiştir. Araştırmacılar hidrojel uygulanan asmalarda yeniden sulama sonrasında daha yüksek fotosensetik performans ve daha iyi bitkisel gelişim bildirmiştir.



Şekil 3. Farklı hidrojel uygulama oranlarına bağlı olarak dört haftalık deney süresince bitkilerin klorofil içeriğinde (SPAD) meydana gelen değişimler

Genel olarak değerlendirildiğinde, çalışma süresince klorofil içeriğinde uygulamalardan bağımsız olarak zamana bağlı bir azalma eğilimi gözlenmiştir. Bununla birlikte, %3,75 hidrojel uygulaması özellikle üçüncü ve dördüncü haftalarda klorofil içeriğinin korunması bakımından diğer uygulamalardan

ayrılmıştır. Bu durum, yüksek hidrojel uygulama oranının deney süresince bitkilerin klorofil düzeylerinin korunmasına katkı sağlayabileceğini ve kuraklık koşulları altında bitki büyümesini koruyabileceğini düşündürmektedir.

SONUÇ

Her 14 günde bir sulama uygulanan su kısıtı koşullarında, hidrojel uygulama oranındaki artışın bitki boyu ve klorofil içeriği üzerinde farklı eğilimlere neden olduğu görülmüştür. Hidrojel oranının %1,25'ten %3,75'e yükseltilmesi bitki boyu artışını belirgin şekilde sınırlandırırken, özellikle %3,75 hidrojel uygulaması dört haftalık deney süresince klorofil içeriğinin daha yüksek düzeylerde korunmasını sağlamıştır. Bu durum, hidrojel uygulamasının bitkisel büyüme ve klorofil korunumu üzerinde farklı mekanizmalar aracılığıyla etkili olabileceğini düşündürmektedir. Yüksek hidrojel oranlarında gözlenen düşük boy artışı, kök bölgesindeki su-hava dengesinin veya fiziksel koşulların değişmesiyle ilişkili olabilirken, aynı uygulamada daha yüksek SPAD değerlerinin korunması, hidrojelin suyun kök bölgesinde tutulmasına katkıda bulunarak bitkinin fizyolojik durumunu belirli ölçüde desteklemiş olabileceğini düşündürmektedir. Bununla birlikte, hidrojel uygulamasının etkinliğinin uygulama oranına ve bitki-su ilişkilerine bağlı olduğu ve yüksek hidrojel oranlarının her zaman daha yüksek bitki gelişimi ile sonuçlanmadığı görülmektedir.

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HİDROJEL MİKROKÜRELERİNİN BİBER BİTKİSİ BÜYÜME PERFORMANSI VE KLOROFİL İÇERİĞİNE ETKİSİ

THE EFFECT OF HYDROGEL MICROSPHERES ON THE GROWTH PERFORMANCE AND CHLOROPHYLL CONTENT OF PEPPER PLANTS

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ÖZET

Biber bitkisi, özellikle kuraklık ve tarımsal su kıtlığı gibi stres koşullarına karşı hassasiyet göstermekte olup, bu durum tarımsal verimliliği olumsuz etkilemektedir. Kuraklık, bitkilerin su alımını kısıtlayarak büyüme ve gelişim süreçlerini engellerken, sürdürülebilir tarım için su yönetimi ve bitki dayanıklılığını artıran teknolojik çözümler büyük önem taşımaktadır. Hidrojel mikroküreleri, yüksek su tutma kapasiteleri ve kontrollü su salınım özellikleri sayesinde, kuraklık stresine karşı bitkilerin su ihtiyacını karşılamada ve büyüme performansını iyileştirmede potansiyel bir araç olarak öne çıkmaktadır. Biber bitkisi, tarımsal üretimde önemli bir yere sahip olup, su kıtlığı koşullarında bitki büyümesini ve verimini artırmak amacıyla çeşitli biyoteknolojik yöntemler araştırılmaktadır. Bu çalışma, sodyum aljinat ve polivinil alkol kullanılarak hazırlanan hidrojel mikrokürelerinin biber bitkisinin büyüme performansı ve klorofil içeriği üzerindeki etkilerini değerlendirmeyi amaçlamaktadır. Eşit boy ve büyüme evresindeki biber bitkileri torf ve hidrojel içeren saksılara ekilmiş ve 14 günde bir sulama yapılarak 28 gün süreyle yetiştirilmiştir. Çalışmada kullanılan hidrojeller, sodyum aljinat (SA) ve polivinil alkol (PVA) polimerleri kullanılarak hazırlanmış ve saksılara eklenmiştir. Bitkilerin ekim sonrasındaki ve hasat öncesi boyları ölçülmüş, ayrıca haftalık klorofil içerikleri bir klorofil metre ile belirlenmiştir. Elde edilen sonuçlara göre, kontrol grubunda maksimum boy artışı %22 olarak belirlenirken, hidrojel uygulamalarında minimum boy artışı %1,25 hidrojelde %7 olarak tespit edilmiştir. Klorofil içeriğinde ise maksimum artış %16 ile %3,75 hidrojel uygulamasında gözlenmiş, minimum artış ise %1,25 hidrojel uygulamasında %3 olarak kaydedilmiştir. Ayrıca, %2,5 hidrojel uygulamasının klorofil içeriğinde anlamlı bir değişiklik yaratmadığı belirlenmiştir. Genel olarak, bulgular hidrojelli mikrokürelerin biber bitkisinin büyümesi ve klorofil içeriği üzerinde konsantrasyona bağlı etkileri olduğunu ve sınırlı sulama koşullarında su yönetimi stratejisi olarak potansiyel taşıdığını göstermektedir.

Anahtar Kelimeler: Biber, Hidrojel, Klorofil, Su kısıtı, Sodyum aljinat,

ABSTRACT

Pepper plants are sensitive to drought and agricultural water scarcity, which can adversely affect plant growth and productivity. Therefore, sustainable water management strategies and technologies that enhance plant resilience to water limitation are of increasing importance. Hydrogel microspheres, owing to their high water-holding capacity and controlled water-release properties, have considerable potential for improving plant performance under water-limited conditions. This study aimed to evaluate the effects of hydrogel microspheres prepared from sodium alginate (SA) and polyvinyl alcohol (PVA) on the growth performance and chlorophyll content of pepper plants. Pepper plants with uniform height and growth stage were cultivated in pots containing peat and different hydrogel concentrations for 28 days, with irrigation applied once every 14 days. Plant height was measured after planting and immediately before harvest, while chlorophyll content was monitored weekly using a chlorophyll meter. The results showed that the maximum increase in plant height was 22% in the control treatment, whereas the lowest increase among the hydrogel treatments was 7% at the 1.25% hydrogel concentration. In terms of chlorophyll content, the highest increase (16%) was observed at the 3.75% hydrogel concentration, while the lowest increase (3%) was recorded at 1.25% hydrogel. Notably, the 2.5% hydrogel treatment did not cause a significant change in chlorophyll content. Overall, the findings indicate that hydrogel microspheres have concentration-dependent effects on pepper plant growth and

chlorophyll content and may have potential as a water management strategy under limited irrigation conditions.
Keywords: Chlorophyll, Hydrogel, Pepper, Sodium alginate, Water-scarcity

GİRİŞ

Su kıtlığı, özellikle artan sıcaklıklar, düzensiz yağış rejimleri ve uzun süreli kuraklık dönemlerinin tarımsal üretimde su kullanılabilirliğini sınırlandırdığı bölgelerde, bitkisel üretkenliği kısıtlayan başlıca faktörlerden biridir. Su yetersizliği, bitkilerin su alımını ve taşınımını sınırlandırarak hücre genişlemesi, yaprak gelişimi ve fotosentetik aktivite gibi temel fizyolojik süreçleri olumsuz etkileyebilmekte; buna bağlı olarak bitki büyümesi, biyokütle oluşumu ve verimde azalmalar meydana gelebilmektedir. Bu nedenle, sınırlı su koşullarında bitkilerin büyümesini sürdürebilmesini sağlayan ve su kullanım etkinliğini artıran sürdürülebilir uygulamaların geliştirilmesi, iklim değişikliğine dayanıklı tarımsal üretim sistemleri açısından giderek daha fazla önem kazanmaktadır. Özellikle su tutma kapasitesini artıran materyallerin kullanımı, sulama suyunun daha etkin değerlendirilmesi ve bitkilerin su kısıtına karşı performansının korunması açısından önemli bir yaklaşım olarak değerlendirilmektedir. Nitekim süper emici polimerlerin toprakta suyun tutulmasını artırarak su kullanım etkinliğini ve bitki gelişimini destekleyebileceği bildirilmiştir (El Idrissi vd., 2023).

Biber (*Capsicum annuum* L.), hem taze tüketim hem de işlenmiş ürün olarak yaygın şekilde yetiştirilen ve ekonomik öneme sahip sebze türlerinden biridir. Bununla birlikte, biber bitkileri su yetersizliğine karşı duyarlı olup, yetersiz su temini bitkilerin vejetatif gelişimini ve fizyolojik performansını olumsuz etkileyebilmektedir. Su kısıtı altında bitkilerde fotosentetik aktivitenin ve yaprak gelişiminin azalması, büyüme süreçlerinin sınırlandırılmasına neden olabilmektedir. Bu nedenle, kök bölgesinde yeterli suyun korunması, özellikle uzun sulama aralıklarında biber bitkisinin büyüme performansının sürdürülebilmesi açısından önem taşımaktadır. Bunun yanında, klorofil içeriği bitkilerin fizyolojik durumunun değerlendirilmesinde önemli bir gösterge olup, fotosentetik kapasite ve çevresel streslere verilen yanıtlarla yakından ilişkilidir. Bu nedenle bitki boyu ve klorofil içeriğinin birlikte değerlendirilmesi, su kısıtı altında uygulanan su yönetimi stratejilerinin etkinliğinin belirlenmesinde faydalı olabilmektedir.

Bitkilerin suya erişiminin iyileştirilmesine yönelik yaklaşımlar arasında, süper emici polimerlerin ve hidrojellerin toprak veya yetiştirme ortamına uygulanması son yıllarda dikkat çekmektedir. Hidrojeller, yapılarında yüksek miktarda su tutabilen üç boyutlu hidrofilik polimerik ağ yapılarıdır. Toprağa veya yetiştirme ortamına uygulandıklarında, sulama sırasında suyu absorbe ederek geçici su rezervuarları oluşturabilmekte ve ortamın kurumasıyla birlikte tuttukları suyu kademeli olarak serbest bırakabilmektedir. Bu özellikleri sayesinde hidrojellerin kök bölgesinde suyun daha uzun süre tutulmasına, su kayıplarının azaltılmasına ve sulama aralığının uzatılmasına katkı sağlayabileceği düşünülmektedir. Nitekim hidrojellerin su kısıtı koşullarında toprak su tutma kapasitesini ve bitki performansını iyileştirme potansiyeli farklı çalışmalarla ortaya konmuştur. Örneğin, sodyum aljinat esaslı süper emici bir hidrojelin su tutma kapasitesini artırdığı ve su stresi altında bitki boyu, gövde çapı, yaprak sayısı, klorofil içeriği ve biyokütle gibi büyüme parametrelerini olumlu yönde etkilediği bildirilmiştir (El Idrissi vd., 2023). Hidrojellerin tarımsal uygulamalardaki etkinliği; kimyasal bileşim, polimer yapısı, çapraz bağlanma özellikleri, şişme kapasitesi ve uygulama dozuna bağlı olarak değişebilmektedir. Bu kapsamda, uygun su tutma, su salınımı ve stabilite özellikleri elde etmek amacıyla doğal ve sentetik polimerlerin yanı sıra farklı polimer kombinasyonları da araştırılmaktadır. Doğal kaynaklı bir polisakkarit olan sodyum aljinat (SA), hidrofilik yapısı, yüksek su tutma kapasitesi, biyobozunurluğu ve biyouyumluluğu nedeniyle hidrojel üretiminde öne çıkan materyallerden biridir. Aljinat esaslı hidrojellerin su kısıtı altında suyun kök bölgesinde tutulmasını artırarak bitki gelişimini destekleyebildiği bildirilmektedir. Pettinelli vd. (2024), sodyum aljinat esaslı bir hidrojelin su tutma özelliklerinin yanı sıra su stresi altında bitki gelişimini destekleyebildiğini ve yaprakların korunmasına olumlu katkı sağlayabildiğini ortaya koymuştur.

Polivinil alkol (PVA) ise hidrofilik yapısı, film oluşturma yeteneği ve hidrojel ağ yapısının oluşturulmasına uygun özellikleri nedeniyle hidrojel üretiminde kullanılan sentetik polimerlerden biridir. Sodyum aljinat ile PVA'nın birlikte kullanılması, her iki polimerin özelliklerinden yararlanılarak su tutma ve salınım davranışı kontrol edilebilen hidrojel yapılarının geliştirilmesine olanak sağlayabilir. Polimer kombinasyonlarının kullanılması, yalnızca tek bir polimerin su absorpsiyon kapasitesinin değil, aynı zamanda polimerler arasındaki etkileşimlerin ve oluşan üç boyutlu ağ yapısının da hidrojelin

performansını belirlemesi açısından önemlidir. Bu nedenle SA ve PVA esaslı hidrojel sistemleri, bitkilerin kök bölgesindeki suyun daha etkin yönetilmesine yönelik potansiyel bir materyal grubu olarak değerlendirilebilir. Hidrojel uygulamalarının farklı bitki türlerinde su kısıtı altında bitki performansını iyileştirebildiğini gösteren çalışmalar bulunmaktadır. Örneğin, El Idrissi vd. (2024), sodyum aljinat esaslı süper emici polimerlerin farklı su kısıtı düzeyleri altında domates bitkisinin gelişimini olumlu etkilediğini ve bitki boyu ile klorofil içeriği dahil olmak üzere çeşitli büyüme parametrelerini iyileştirdiğini bildirmiştir. Benzer şekilde, sodyum aljinat esaslı hidrojellerin su kısıtı altında farklı bitki türlerinde suyun tutulmasını artırarak bitki gelişimini destekleyebildiği rapor edilmiştir. Pettinelli vd. (2024), aljinat esaslı hidrojel uygulamasının su yetersizliği koşullarında bitki gelişimini ve biyokütle birikimini desteklediğini göstermiştir. Ayrıca aljinat ve atık kâğıt esaslı biyobozunur bir hidrojelin ayçiçeğinde toprak su tutma kapasitesini artırarak kuraklık stresinin olumsuz etkilerini azaltabildiği ve bitki gelişimini desteklediği bildirilmiştir (Gomaa ve Aldaby, 2023). Bu sonuçlar, hidrojellerin yalnızca toprakta suyun tutulmasını sağlayan materyaller olmadığını, aynı zamanda su kısıtı altında bitkilerin fizyolojik ve büyüme performansının korunmasına katkıda bulunabileceklerini göstermektedir. Bununla birlikte, mevcut literatürde hidrojellerin bitki gelişimi ve su stresi üzerindeki etkileri konusunda önemli ilerlemeler kaydedilmiş olsa da, hidrojelin kimyasal bileşimi ve uygulama dozunun bitki yanıtları üzerindeki etkilerinin bitki türüne ve yetiştirme koşullarına bağlı olarak değişebildiği görülmektedir. Özellikle SA ve PVA kombinasyonuyla hazırlanan hidrojel mikrokürelerinin biber (*Capsicum annuum* L.) bitkisinde uzun sulama aralıkları altında büyüme ve fizyolojik performans üzerindeki etkilerine ilişkin çalışmaların sınırlı olduğu görülmektedir. Ayrıca, hidrojel uygulamalarında dozun artırılmasının her zaman bitki performansında doğrusal bir iyileşme sağlamaması, optimum uygulama konsantrasyonlarının belirlenmesini gerekli kılmaktadır. Bu nedenle, farklı hidrojel konsantrasyonlarının bitki büyümesi ve klorofil içeriği üzerindeki etkilerinin birlikte değerlendirilmesi, hidrojellerin su kısıtı altında kullanım potansiyelinin daha iyi anlaşılması açısından önem taşımaktadır. Bu çalışma, sodyum aljinat ve polivinil alkol kullanılarak hazırlanan hidrojel mikrokürelerinin uzun süre sulanmaması durumunda biber bitkisinin büyüme ve fizyolojik performansı üzerindeki etkilerini değerlendirmeyi amaçlamaktadır. Bu kapsamda, eşit gelişim düzeyine sahip biber bitkileri farklı hidrojel konsantrasyonları (%1,25-%2,5-%3,75 a/a) içeren torf ortamında 28 gün boyunca yetiştirilmiş ve bitkilere 14 günlük sulama aralıkları uygulanmıştır. Hidrojel uygulamalarının etkinliği, bitki boyundaki değişim ve haftalık klorofil içeriği üzerinden değerlendirilmiştir. Çalışmanın temel hipotezi, SA-PVA esaslı hidrojel mikrokürelerinin kök bölgesinde suyun tutulmasını artırarak uzun sulama aralıkları altında biber bitkisinin büyüme ve klorofil içeriğinin korunmasına katkı sağlayabileceği ve bu etkinin hidrojel konsantrasyonuna bağlı olarak değişebileceğidir. Elde edilen sonuçların, hidrojel uygulama dozlarının optimize edilmesine ve sınırlı sulama koşullarında biber yetiştiriciliği için sürdürülebilir su yönetimi stratejilerinin geliştirilmesine katkı sağlaması beklenmektedir.

MATERYAL-YÖNTEM

Hidrojel sentezi ve Karakterizasyonu

Çalışmada kullanılmak üzere, sodyum aljinat (SA) ve polivinil alkol (PVA) polimerlerinin çözeltisi kullanılarak fiziksel çapraz bağlama yoluyla polimerik kompozit hidrojel boncukları sentezlenmiştir. Kısaca, hidrojel boncukların üretimiyle ilgili olarak, %3 (a/h) PVA ve %2 (a/h) sodyum aljinat polimerleri, homojen bir çözelti elde etmek için 25 °C'de 2 saat boyunca manyetik karıştırıcıda karıştırılmıştır. Daha sonra çözelti, %5 (a/h) $CaCl_2$ çözeltisine damla damla eklenmiş ve manyetik karıştırıcıda (100 rpm) gece boyunca sürekli olarak karıştırılmıştır. Hidrojel boncukları $CaCl_2$ çözeltisinden alınarak birkaç kez deiyonize su ile yıkanmış ve bitki denemelerinde kullanılmak üzere kuruma ve bozulmaları engellemek için saf su içerisinde buzdolabında saklanmıştır. Üretilen hidrojeller oda koşullarında 5 gün kurutulduktan sonra Taramalı Elektron Mikroskopisi (SEM) ile analiz edilerek yüzey yapıları belirlenmiştir.

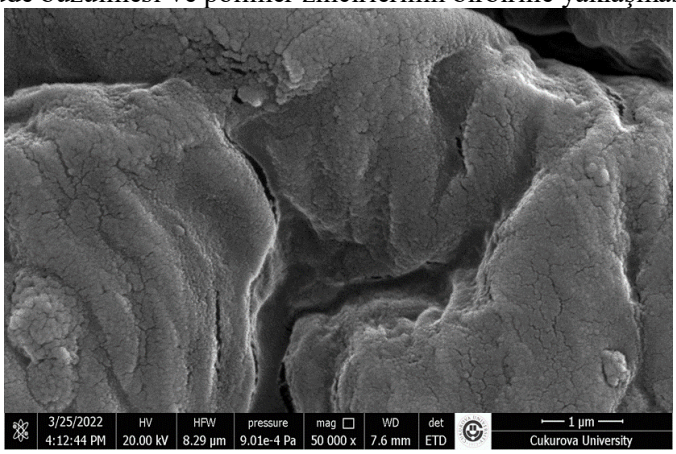
Bitki Denemeleri

Her saksıya 400 g torf ve üretilen hidrojellerden farklı miktarlarda (%1,25-%2,5-%3,75 a/a) eklenerek eşit boydaki biber fideleri ekilmiştir. Can suyunun verilmesinin ardından bitki boyları ölçülmüş, 14 gün ara ile iki sulama gerçekleştirilmiş ve bitkiler 28 gün boyunca büyütülmüştür. Her saksıdan haftalık klorofil ölçümleri Konica-Minolta Klorofil metre ile gerçekleştirilmiştir. İkinci sulamanın ardından son bitki boyları da ölçülmüştür.

BULGULAR

Hidrojel Karakterizayonu

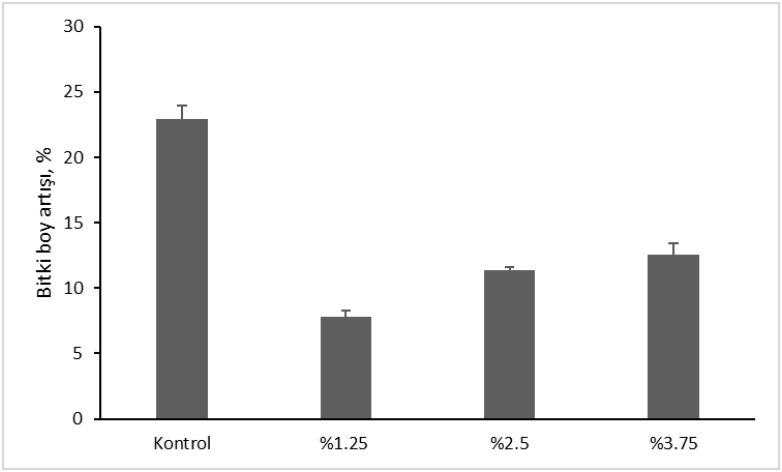
Sentezlenen PVA/SA hidrojelinin SEM görüntüsü (Şekil 1), yüzey morfolojisinin genel olarak yoğun, kompakt ve heterojen bir yapı sergilediğini göstermektedir. Yüzey düzensiz biçimde dağılmış mikro ölçekte boşluklar, çatlak benzeri yapılar ve kıvrımlı yüzey bölgeleri gözlenmektedir. Yüzeydeki bu morfolojik düzensizlikler, polivinil alkol ve sodyum aljinat polimer zincirleri arasındaki etkileşimler sonucunda oluşan yoğun polimerik ağ yapısının bir göstergesi olarak değerlendirilebilir. Özellikle, birbirine yaklaşan/katlanan polimerik bölgeler arasında dar ve düzensiz boşluklar dikkat çekmektedir. Bununla birlikte, açık ve birbirine bağlı, geniş gözenekli bir yapı yerine daha sıkı paketlenmiş ve düşük makro-gözenekliliğe sahip bir morfoloji de dikkat çekmektedir. Bu durum, PVA/SA matrisinin kurutma sonrasında önemli ölçüde büzülmesi ve polimer zincirlerinin birbirine yaklaşmasıyla ilişkili olabilir.



Şekil 1. Sentezlenen PVA/SA hidrojeline ait SEM görüntüsü

Bitki Boyu ve Klorofil İçeriği

Bitki boyu artışı değerlendirildiğinde, kontrol grubunda yaklaşık %23 ile en yüksek artış gözlenmiştir. Hidrojel uygulamalarında ise bitki boyu artışı %1,25, %2,5 ve %3,75 hidrojel oranlarında sırasıyla yaklaşık %8, %11 ve %13 olarak belirlenmiştir (Şekil 2). Hidrojel oranının %1,25'ten %3,75'e artırılmasıyla bitki boyu artışında kademeli bir yükselme eğilimi gözlenmesine rağmen, hidrojel uygulamalarındaki değerler kontrol grubunun altında kalmıştır. En düşük bitki boyu artışı %1,25 hidrojel uygulamasında gözlenirken, en yüksek hidrojel uygulaması olan %3,75 oranında bu değer yaklaşık %13'e ulaşmıştır. Bu sonuçlar, 14 günlük sulama aralığı uygulanan 28 günlük yetiştirme döneminde hidrojel oranının bitki boyu gelişimi üzerinde farklı düzeylerde etkili olabileceğini ve hidrojel oranındaki artışın düşük uygulama oranına kıyasla bitki boyu artışını destekleyen bir eğilim oluşturduğunu göstermektedir.



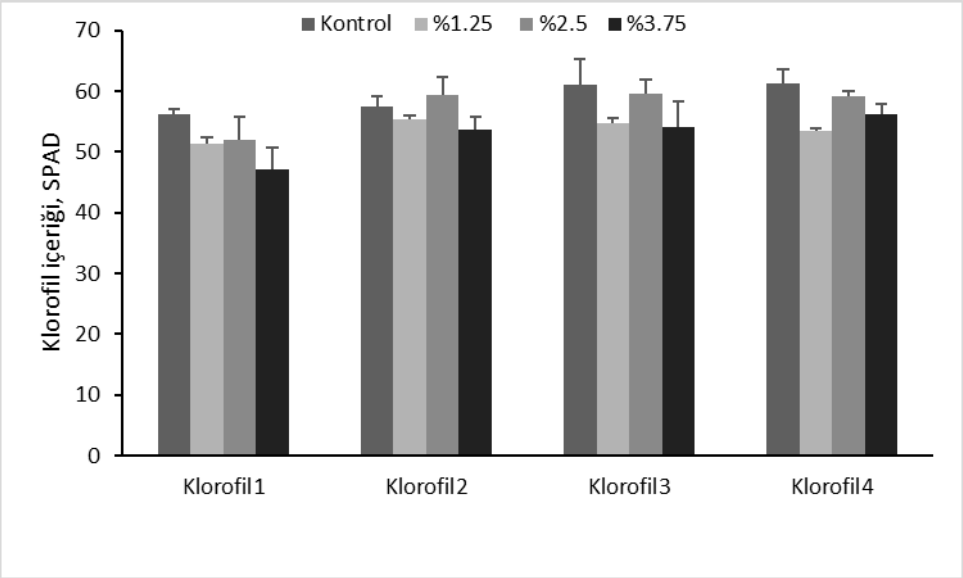
Şekil 2. Farklı hidrojel uygulamalarının (%1,25, %2,5 ve %3,75, a/a) 28 günlük yetiştirme süresi sonunda biber (*Capsicum annuum* L.) bitkilerinde bitki boyu artışı (%) üzerine etkisi

28 günlük yetiştirme dönemi sonunda biber bitkilerinin bitki boyundaki artış incelendiğinde, kontrol grubunda yaklaşık %23 ile en yüksek boy artışı gözlenmiştir (Şekil 2). Hidrojel uygulamalarında ise bitki boyu artışı %1,25, %2,5 ve %3,75 (a/a) hidrojel uygulamalarında sırasıyla yaklaşık %8, %11 ve %13 olarak belirlenmiştir. Buna göre, hidrojel uygulamalarında en düşük bitki boyu artışı %1,25 hidrojel uygulamasında gözlenirken, hidrojel miktarının artırılmasıyla bitki boyu artışında kademeli bir yükselme eğilimi ortaya çıkmıştır. Bununla birlikte, hidrojel uygulamalarının hiçbirinde kontrol grubundaki boy artışına ulaşılamamıştır. Hidrojellerin tarımsal yetiştirme ortamlarında kullanılmasının temel avantajlarından biri, suyu absorbe ederek kök bölgesinde tutulmasını ve ortamın kurumasıyla birlikte kontrollü biçimde kullanılabilir hale gelmesini sağlamalarıdır. Bu özellikleri nedeniyle hidrojellerin özellikle suyun sınırlı olduğu koşullarda toprakta kullanılabilir su miktarını ve bitki gelişimini destekleme potansiyeline sahip olduğu bildirilmektedir. Piccoli et al. (2024), hidrojellerin yüksek su tutma kapasiteleri sayesinde toprakta kullanılabilir suyun artırılmasına ve özellikle orta düzeyde su kısıtı koşullarında bitki performansının korunmasına katkı sağlayabileceğini bildirmiştir.
Bununla birlikte, mevcut çalışmada hidrojel uygulamalarının kontrol grubuna kıyasla daha düşük bitki boyu artışı göstermesi, hidrojel kullanımının her koşulda doğrudan daha yüksek vejetatif gelişim sağlayacağı şeklinde yorumlanmamalıdır. Hidrojelin bitki gelişimi üzerindeki etkisi; hidrojelin kimyasal yapısı, uygulama oranı, yetiştirme ortamı ve suyun ortamda bulunabilirliği gibi birçok faktöre bağlı olarak değişebilmektedir. Nitekim Gosukonda vd. (2024), *Capsicum annuum* bitkileriyle yürüttükleri çalışmada hidrojel tipinin ve konsantrasyonunun bitki boyu üzerindeki etkilerinin farklılık gösterebildiğini ve bazı hidrojel konsantrasyonlarının kontrol grubundan daha yüksek büyüme sağlarken, bazı uygulamaların daha düşük performans gösterdiğini bildirmiştir. Bu araştırmacılar, uygun hidrojel konsantrasyonunun su ve besin alımını destekleyen daha elverişli bir kök bölgesi oluşturabileceğini belirtmiştir. Bu çalışmada da hidrojel oranının %1,25'ten %2,5 ve %3,75'e yükseltilmesiyle bitki boyu artışında gözlenen kademeli yükselme, hidrojel dozunun bitki gelişimi açısından önemli olabileceğini düşündürmektedir. Özellikle %1,25 hidrojel uygulamasında gözlenen yaklaşık %8'lik artışa karşılık %3,75 uygulamasında yaklaşık %13'lük artış elde edilmesi, yüksek hidrojel oranlarının mevcut yetiştirme koşullarında düşük uygulama oranına kıyasla bitki boyu gelişimini destekleyen bir eğilim oluşturabileceğini göstermektedir. Ancak kontrol grubunun yaklaşık %23'lük artışla en yüksek değeri göstermesi, hidrojel uygulamalarının bu çalışmada bitki boyu açısından kontrolün üzerinde bir performans sağlamadığını ortaya koymaktadır. Deneme süresince yetiştirilen biber bitkilerine ait görsel Şekil 3'te verilmiş olup kontrol bitkileri ile hidrojel eklenmiş saksılardaki bitki boyu farklılıkları net bir şekilde görülmektedir. Benzer şekilde, *Capsicum annuum* üzerinde yapılan başka bir çalışmada hidrojel içeren yetiştirme ortamlarının bitki gelişimi üzerindeki etkisinin hidrojel miktarına bağlı olarak değiştiği ve belirli bir uygulama oranının diğer oranlara göre daha iyi büyüme sonuçları sağlayabildiği bildirilmiştir. Hafiz-Afham vd. (2023), hidrojel içeren ortamda yetiştirilen biberlerde optimum gelişimin belirli bir hidrojel oranında elde edildiğini ve bu etkinin hidrojelin suyu ortamda tutarak bitkinin su kullanımını desteklemesiyle ilişkili olabileceğini belirtmiştir. Bu sonuçlar, mevcut çalışmada hidrojel oranı arttıkça bitki boyu artışında gözlenen kademeli yükselme eğilimiyle genel olarak örtüşmektedir.



Şekil 3. Sentezlenen PVA/SA hidrojelleri eklenmiş ve eklenmemiş bitkilere ait görüntü

Şekil 4'te kontrol grubunun klorofil içeriğinin yaklaşık 56 SPAD ile başlamakta ve ikinci haftada yaklaşık 58 SPAD'a, üçüncü haftada ise yaklaşık 61 SPAD değerine yükseldiği görülmektedir. Dördüncü haftada da yaklaşık 61 SPAD ile yüksek seviyesini koruduğu görülmektedir. Bu durum, 28 günlük yetiştirme süresince kontrol bitkilerinde klorofil içeriğinin genel olarak artan ve daha sonra yüksek seviyede sabitlenen bir eğilim gösterdiğini ortaya koymaktadır. %1,25 hidrojel uygulamasında klorofil içeriği ilk hafta yaklaşık 51 SPAD iken ikinci haftada yaklaşık 55 SPAD'a yükselmiş, üçüncü haftada yaklaşık 56 SPAD ile en yüksek değerine ulaşmıştır. Dördüncü haftada ise yaklaşık 54 SPAD'a hafif bir gerileme gözlenmiştir. Dolayısıyla bu uygulamada klorofil içeriği başlangıçta artış göstermesine rağmen, çalışmanın son haftasında bir miktar azalma eğilimi gösterdiği belirlenmiştir. %2,5 hidrojel uygulaması ise özellikle dikkat çekici sonuçlar göstermiştir. İlk haftada yaklaşık 52 SPAD olan klorofil içeriği ikinci haftada yaklaşık 59 SPAD'a yükselmiş ve üçüncü haftada yaklaşık 60 SPAD ile yüksek seviyesini korumuştur. Dördüncü haftada ise yaklaşık 59 SPAD değerine hafif bir düşüş görülmüştür. Bu uygulama, hidrojel grupları içerisinde özellikle son haftalarda kontrol grubuna en yakın klorofil değerlerini göstermektedir. %3,75 hidrojel uygulamasında ise ilk hafta yaklaşık 47 SPAD ile tüm uygulamalar arasında en düşük klorofil değeri görülmüştür. Bununla birlikte ikinci haftada yaklaşık 54 SPAD'a yükselmiş ve üçüncü haftada bu düzeyi korumuştur. Dördüncü haftada ise yaklaşık 56 SPAD değerine ulaşarak başlangıç değerine kıyasla belirgin bir yükselme göstermiştir. Dolayısıyla yüksek hidrojel oranında başlangıçta düşük olan klorofil içeriğinin zaman içerisinde toparlandığı ve çalışma sonunda ilk haftaya göre daha yüksek bir düzeye ulaştığı görülmektedir. Sonuç olarak, uygulamalar arasında farklı zamansal eğilimler gözlenmiştir. Genel olarak, 14 günlük sulama aralığı uygulanan 28 günlük yetiştirme döneminde hidrojel uygulamalarının klorofil içeriğini zaman içerisinde koruduğu veya arttırdığı görülmüştür. Özellikle %2,5 ve %3,75 hidrojel uygulamalarında birinci haftaya kıyasla çalışma sonunda daha yüksek klorofil değerlerine ulaşılması dikkat çekmiştir. Bu sonuçlar, 14 günlük sulama aralığı uygulanan 28 günlük yetiştirme döneminde hidrojel uygulamalarının klorofil içeriğinde özellikle zaman içerisinde korunma veya artış eğilimi oluşturduğunu göstermektedir. Özellikle %2,5 ve %3,75 hidrojel uygulamalarında birinci haftaya göre dördüncü haftada daha yüksek SPAD değerlerinin elde edilmesi dikkat çekicidir. Bununla birlikte, kontrol grubunun klorofil içeriği tüm haftalarda genel olarak hidrojel uygulamalarının üzerinde veya bunlara yakın seyretmiş ve üçüncü-dördüncü haftalarda yaklaşık 61 SPAD ile en yüksek değerleri korumuştur.



Şekil 4. Farklı hidrojel oranlarının (%1,25, %2,5 ve %3,75, a/a) biber (*Capsicum annuum* L.) bitkilerinin dört haftalık klorofil içeriğine etkisi

Klorofil içeriğinin bitkinin su durumu ve fotosentetik performansıyla ilişkili olduğu bilinmektedir. Biber üzerinde yapılan çalışmalar, su durumundaki değişimlerin klorofil içeriği ve diğer fizyolojik özellikler üzerinde etkili olabileceğini göstermektedir. Örneğin Goto vd. (2021), *Capsicum chinense* bitkilerinde farklı toprak su koşullarının yaprak su potansiyeli ve stomatal iletkenliğin yanı sıra klorofil içeriğini de etkilediğini bildirmiştir. Duah vd. (2021) ise farklı su temini koşullarında yetiştirilen biber çeşitlerinde

SPAD değerlerinin su uygulamalarına ve çeşide bağlı olarak değişebildiğini göstermiştir. Bu çalışmalar, mevcut çalışmada haftalar arasında gözlenen SPAD değişimlerinin yalnızca hidrojel uygulaması açısından değil, bitkilerin zaman içerisinde değişen su durumuna ve gelişme sürecine verdiği fizyolojik yanıtlar açısından da değerlendirilmesi gerektiğini göstermektedir. Hidrojellerin klorofil içeriği üzerindeki olası etkisi ise büyük ölçüde kök bölgesindeki suyun korunması ile ilişkilendirilebilir. Hidrojellerin suyu tutarak kök bölgesindeki nemin daha uzun süre korunmasına katkı sağlayabildiği ve böylece bitkilerin suya erişimini destekleyebildiği bildirilmektedir. Özellikle Gosukonda vd. (2024), *Capsicum annuum* bitkilerinde hidrojel içeren yetiştirme ortamlarının toprak nemini kontrol grubuna kıyasla daha iyi koruduğunu göstermiştir. Aynı çalışmada hidrojel konsantrasyonuna bağlı olarak bitki büyümesinde farklı yanıtlar gözlenmiştir.

SONUÇLAR

Bitki boyu ve klorofil sonuçları birlikte değerlendirildiğinde, hidrojel uygulamalarının bu iki gelişim göstergesi üzerinde tamamen aynı yönde bir yanıt oluşturmadığı görülmektedir. Bitki boyu açısından kontrol grubu yaklaşık %23'lük artışla en yüksek değeri gösterirken, hidrojel uygulamalarında %1,25'ten %3,75'e doğru artan bir büyüme eğilimi gözlenmiştir. Buna karşılık, klorofil içeriğinde özellikle %2,5 ve %3,75 hidrojel uygulamalarında çalışma süresinin ilerleyen dönemlerinde başlangıç değerlerine göre daha yüksek SPAD değerleri elde edilmiştir. Bu durum, hidrojel uygulamalarının bitki büyümesini doğrudan artırmaktan ziyade, belirli uygulama oranlarında kök bölgesindeki suyun daha uzun süre korunmasına bağlı olarak bitkinin fizyolojik durumunun sürdürülmesine katkıda bulunabileceğini düşündürmektedir.

Öte yandan, biber bitkisinde hidrojel kullanımına yönelik çalışmaların sonuçları da hidrojel uygulamalarının her zaman kontrol grubuna göre daha yüksek büyüme sağlamadığını göstermektedir. Bu çalışmada da yüksek hidrojel oranlarında klorofil değerlerinin zaman içerisinde korunduğu/arttığı ancak bitki boyu artışının kontrol grubunun altında kaldığı belirlenmiştir. Genel olarak, 28 günlük yetiştirme süresince 14 günlük sulama aralığı uygulanan koşullarda, hidrojel oranının artırılması bitki boyu artışında %1,25 uygulamasına kıyasla yükselen bir eğilim oluşturmuş; klorofil içeriğinde ise özellikle %2,5 ve %3,75 hidrojel uygulamalarında zaman içerisinde daha yüksek değerler gözlenmiştir. Bununla birlikte, kontrol grubunun hem bitki boyu artışında hem de klorofil içeriğinde genel olarak daha yüksek değerlere sahip olması, kullanılan hidrojel uygulama oranlarının bu deney koşullarında bitki gelişimini kontrolün üzerine taşımadığını göstermektedir. Bu sonuçlar, SA-PVA esaslı hidrojel mikroküre lerinin etkisinin uygulama dozuna ve ölçülen bitki gelişim parametresine bağlı olarak değişebileceğini ve özellikle uzun sulama aralıklarında hidrojel uygulamalarının değerlendirilmesinde yalnızca büyüme değil, klorofil gibi fizyolojik göstergelerin de dikkate alınması gerektiğini ortaya koymaktadır.

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HAZARDOUS CARGO OPERATIONS AT LIQUID BULK TERMINALS: A CASE STUDY FROM THE PERSPECTIVE OF INTERNATIONAL TRADE AND SUPPLY CHAIN CONTINUITY

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ABSTRACT
Maritime transport is an important part of international business where the ports and terminals are important nodes of the global business chain. In the case of hazardous liquid bulk cargo terminals, disruptions in their operations due to accidents like fire and explosion could have impacts on cargo movement and the continuity of the business chain along with the environmental and occupational safety issues. The objective of this research is to identify the risks related to dangerous cargo handling activities in liquid bulk terminals and review the safety measures used considering both national and international regulations from the viewpoint of business continuity and logistics security. The qualitative case study approach was used in this study where liquid bulk terminal in Türkiye served as the subject of the research. The primary data were gathered using semi-structured interviews conducted with the operations supervisor and occupational health and safety professional participating in dangerous cargo handling activities. From the results, it can be noted that the operational risks are addressed in a proactive manner. The international technical standards regulate the terminal infrastructure, and maintenance of tanks and pipelines help to ensure operation safety. The engineering controls, such as the prevention of static electricity, use of pressure-vacuum valves, and cooling for temperature sensitive cargo also contribute to the prevention of fire and explosion hazards. Moreover, the communication-based safety measures such as the briefings on risks and safety and tool box talks assist in addressing the human related operational risks. According to the study, the approach to safety management at dangerous liquid bulk terminals is not limited to regulatory requirements only. The use of technology, risk management, safety culture, and contingency planning is very important for continuity of terminal operations and for preventing logistical problems. This paper has made an important contribution to literature on port management by connecting safety procedures in the terminal with continuity of its operations.
Keywords: Hazardous Cargo Logistics, International Trade, Liquid Bulk Terminals, Risk Management, Supply Chain Continuity.

INTRODUCTION
A substantial share of the raw materials that industries use in the global economy move via the seas. Materials that are dangerous and are used in certain industries such as the chemical, plastics, agricultural, and cosmetics industries constitute a large portion of sea logistics. Dangerous materials not only have health and environmental hazards but may also be flammable, explosive, and poisonous.
A liquid bulk terminal refers to a port facility that has the necessary equipment needed to store and later on transport large amounts of liquids and liquefied gases. This includes crude oil, petroleum products, chemicals, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and others (Menon, 2024).
The transport of hazardous materials in marine vessels makes up a considerable portion of the transportation mode. The employment of such in the transport of hazardous cargo depends mostly on its safety and economical nature. Hazardous materials may be considered as raw materials or end-products of certain industries such as chemicals, plastics, agriculture, and cosmetics (Yeğin, 2023).
Dangerous goods have diverse effects on human life and the environment, which include being explosive, corrosive, flammable, toxic, and infectious. Dangerous cargo that may be in solid or liquid form can be moved through bulk transport, containerized, or through RO-ROs and tankers. For the

purposes of minimizing harm to human life and the environment as well as reducing accidents related to such cargo handling, the IMO has developed the IMDG Code. The IMDG Code forms a good platform in classifying dangerous goods, determining proper packaging, transportation means, and operation requirements for each hazard category (Ünal & Usluer, 2015).

Cargo considered hazardous, from the handling of which from port to ship and vice versa, is dangerous for the environment and the health of the personnel involved. In case of any accidents involving the cargo while being handled, there will be severe impacts on the port facilities, marine environment, and human health (Boran & Alkan, 2018). Special attention should be paid to loading, unloading, filling, moving, and packing the hazardous materials. Corrective and preventive actions must be taken to eliminate the operational risks (Tatar & Özer, 2018).

Corrective and preventive actions are critical parts of occupational health and safety management systems and one of the main methods to manage the risks associated with the hazardous cargo handling at port facilities (Yeğin & Yorulmaz, 2023).

LITERATURE REVIEW

Romer et al. (1995) have studied the pattern of occurrence of accidents and fatalities resulting from hazardous cargoes being transported by water. They looked at 2,781 fatal accidents with hazardous cargo on maritime transport and compared them with fatal hazardous cargo accidents in other modes of transport. This study was carried out with particular emphasis on the influence of cargo type, tanker type, and geographic location on fatality pattern.

The use of GIS was employed by Buhur (2007) to investigate the risks created by the carriage of dangerous cargo in the Istanbul Straits and their surroundings. According to this study, Sarıyer (Central and Tarabya), Yeniköy and İstinye were among the areas under the highest risk category in respect of casualties in case of an incident. Measures recommended by the researcher in dealing with such risks included the requirement of pilotage of vessels carrying dangerous cargo, provision of alternative locations for facilities exposed to risks and transporting some of the cargo using pipelines.

Zorba (2009) researched the safety culture in the prevention of accidents related to dangerous goods. This study was carried out with regard to safety skills and training levels of both personnel and management engaged in handling dangerous cargo in the container terminals. The main aim of this research was to determine the requirements of the integration of safety culture in the organizational structure.

In 2015, Ünal and Usluer focused on the importance of training for dealing with hazardous cargoes at port facilities. The scientists analyzed the classification and dangers associated with hazardous substances and cargoes, such as explosiveness and flammability, and the hazards which could arise from them in ports. International standards, such as SOLAS, MARPOL, and IMDG Code, and national legal acts were considered. Also, the training framework of Turkish ports and authorized institutions were studied. As a result, the authors came to the conclusion that the number of dangerous goods safety advisers and authorized training institutions in Türkiye was inadequate, especially in public ports. It is necessary to emphasize that the authors suggested improving inspections and aligning training with existing standards to avoid catastrophes similar to the one that occurred in the Port of Tianjin, China.

Sıtkı (2017) investigated maritime logistics of dangerous and perishable cargo through case of the Port of Mersin and analyzed the topic from a statistical perspective on global and national levels. The study emphasized the necessity of adherence of transport operations to national and international laws and stressed the importance of observing occupational safety by personnel of the port and ship.

Mert & Çetinyokuş (2020) concentrated on accident analysis in maritime transportation and revealed that dangerous cargo was especially important for fires and explosions accidents. In Fault Tree Analysis the authors identified human factor, failure of equipment, and electric failures as reasons for accidents. The authors suggested developing emergency plans and collecting statistical data about accidents.

Chen et al. (2020) examined the root causes of accidents taking place during the handling of hazardous cargo in Chinese ports through the use of Formal Concept Analysis (FCA). The results revealed that proper management of storage, infrastructure, and equipment decreased the possibility of accidents. Hence, it was suggested to improve the existing operational management process to decrease the number of accidents.

Kuzu (2021) assessed the sabotage risks and consequences in tankers loaded with propane gas based on a BLEVE analysis through the use of ALOHA software. The results showed that the spread of hazardous

gases over wide distances might be dangerous for the population and the environment. On the basis of the described situation, the author stressed the significance of the operational safety and occupational safety of hazardous cargo transportation at sea.

METHODOLOGY

Research Objective

The study addresses the following research questions:
1. What are the main operational risks encountered during hazardous cargo operations at liquid bulk terminals?
2. What technical, managerial, and human-centred safety practices are used to manage these risks?
3. How do these safety practices contribute to the continuity of terminal operations and the supply chain?
The main objective of this research is to investigate the risks which might appear during the handling and storing of dangerous cargoes in liquid bulk terminals and to evaluate the range of occupational health and safety practices which have been undertaken in order to prevent those risks within the national and international legislation. The study employs a qualitative methodology to look into the risk factors related to the handling and storing of dangerous cargoes as well as the safety practices which have been undertaken as a response to the identified risks at the terminal examined in the case study. Semi-structured interviews and document analysis are the main tools used for this purpose. The current research also focuses on the importance of safety practices in sustaining the operations of the terminal and avoiding possible interruptions of the supply chain.

Data Analysis Method (Case Study)

In order to analyze the operations with hazardous cargoes and safety procedures in the liquid bulk terminals, a case study method, one of the qualitative research techniques, was chosen. The use of case studies allows considering a certain phenomenon in its natural environment and discussing the processes in terms of various perspectives.
As for the empirical section of the research, the considered terminal was seen as a specific example of managing hazardous cargo. Interviews with the officials of the terminal that were conducted by the author using semi-structured technique were analyzed along with the institutional documents, such as the occupational health and safety policy of the terminal and corresponding national and international regulations.

Research Sample

Study area refers to the terminal under investigation, which is where operations involving the liquid cargo take place, as well as those involving dangerous liquid cargo. The terminal was chosen as the setting for the research since it had all the infrastructure for the operations, handled dangerous liquid cargo, and had operational processes, which are pertinent to the aims of the research.
The study group comprised professionals who were engaged in planning, carrying out, and guaranteeing the safety of dangerous liquid cargo operations. These individuals included:
• An Operations Manager, in charge of the technical supervision of the operations
• An Occupational Health and Safety (OHS) Specialist in charge of the risks of the operation
The key factor considered while recruiting respondents is the respondent's experience in working with dangerous cargo operations and safety procedures. In this context, interviewers conducted the interviews with two officials, one of whom had been tasked with managing operations from a technical perspective while the other official handled health and safety issues.

Data Collection Process

Semi-structured interviews, which is a qualitative method of data gathering, were employed in the gathering of the research data. The questionnaire used in the interviews was designed through a comprehensive study of literature, especially regarding the management and storage of dangerous liquid cargoes and possible risks arising from them. According to the literature study, the questions of the questionnaire were classified into various themes.
The questionnaire was administered at the terminal in question to see how dangerous liquid cargoes are managed. The reason for selecting this terminal was that the research was carried out regarding the

management of dangerous liquid cargoes. The data gathering was done on 15 August 2026. Interviews were conducted face-to-face with persons responsible for hazardous material safety and safety plans related to hazardous materials at the port. These interviews took about 120 minutes.

This research was approved by the Social and Human Sciences Research Ethics Committee of the Rectorate of Mersin University on June 30, 2026, within the framework of Decision No. 213 made at the eighth meeting of the Committee. Prior to conducting the interviews, the objectives of the research were explained to the participants along with their freedom of participation. Special care was taken to respect the privacy of the participants' and institution's information. Personal and institutional information related to the identification of the terminal or participants were not included in the manuscript in order to maintain anonymity.

Interview data were analyzed along with the documental and literary data gathered from the relevant institutions. The results were comparatively interpreted in terms of physical and operational risks, dangerous goods operations, environmental and human health risks, safety culture, emergency planning, and operational continuity.

FINDINGS

Findings were analyzed based on the themes below that had been supported from literature review: physical and operational hazards; hazardous cargo operation and chemical reaction hazards of liquid cargo; environmental and human health hazards of hazardous cargo; and safety culture, management system, and personnel training.

General Physical and Operational Risks

In port facilities, where it is universally agreed that there exist many hazards, various precautions have been taken at the particular terminal under consideration in order to prevent hazards both physically and operationally. Since the port facility is a liquid cargo terminal, the use of machinery and cranes is primarily restricted to maintenance, repairs, and manufacturing operations at the tanks. The majority of the traffic in the port facility comprises road tankers, whose daily movement averages about 170 entries and exits. In order to ensure the safety of pedestrians from this traffic, the pedestrian paths are painted yellow and their use is compulsory. Ring vehicles (golf cars) move along segregated pathways, away from vehicle traffic, and at a speed of 20 km/h. The discussion is also on going regarding precautionary actions involving authorities and the municipality such as one-way traffic system planning and provision of a truck parking area for truck traffic in the outside area of the port facility.

Hazards arising out of vapor formation are controlled by scrubbers whereas those related to abrupt change in pressure are controlled by PV valves and pressure transmitters.

Activities performed in confined spaces are governed by strict regulations, especially when it comes to entry into the tanks, which is regarded as a high-risk activity. Prior to entering the tank, its manholes are opened, and the space is initially cleaned with Butterworth machinery to render it gas free. The level of gases and oxygen in the confined space is checked by an OHS worker before granting the confined space entry permit. An observer is present outside the tank at all times, while the OHS staff ensures that the rescue gear, which includes breathing apparatus and the stretcher, is always kept ready for emergencies such as unconsciousness.

Hazardous Cargo Operations and Liquid Cargo Reaction Hazards

There are API (American Petroleum Institute) standards such as API 650 and API 653, which are implemented in a very strict manner to ensure safety for equipment during handling of hazardous cargoes. After completion of construction of the tanks, the in-service inspection of the equipment is done by an outside accredited organisation in the fifth year. The tanks are drained and then undergo periodic inspection in the tenth year with emphasis on shell thickness and welds. Leak tests using hydrostatic method are done in the pipeline every year. Inspection and maintenance of the pumps and PV valves are done periodically by technical staff or through faults generated in the SAP system.

The approximately 25 chemicals that are handled in the facilities have their own lines and no chemical derivatives are transported using the same line. For prevention of accumulation of static charge in the transfer of liquid cargo, the filling process is started with a minimum flow rate of 1 m/s up to submersion of the end of the product line in the liquid. Depending on the conductivity of the cargo, the flow rate is increased up to 4 m/s.

In the case of styrene monomers that might cause polymerization with an increase in the temperature level, the addition of inhibitors is done, and the temperature is kept at 15°C to 18°C through chillers. Should the temperature rise above 25°C, the storage life of the chemical becomes shorter. The primary guideline being followed by the facility is the IBC (International Bulk Chemical) code. Also, a compatibility matrix is used in handling incompatible chemicals that are stored in barrels or IBC tanks. Chemicals like acids and bases that might react with each other and become more hazardous in the case of leakage are not stored next to each other.

Environmental and Human Health Impacts of Hazardous Cargo

Three emergency plans that can be considered as emergency response plans that cover possible spills and accidents at the terminal include occupational safety, prevention of major industrial accidents, and marine pollution prevention plans. In case of any spillage of chemicals into the ocean, the professional company hired by the terminal is called and it is supposed to come to the scene within an hour. But terminal staff does not always wait for assistance. They immediately try to stop the leakage and use containment booms.

These practices are being carried out during annual large scale exercises of firefighting, search and rescue, and first-aid teams, which involve external organizations such as AFAD or fire services.

In order to protect personnel from contacting the chemicals, PPE matrix, which provides information about properties of all the chemicals, is applied. Hard hat, safety footwear, and regular working clothes are mandatory for everyone. During handling corrosive and toxic chemicals, acid-resistant gloves, full-faced masks, face shield, or chemical suits are worn. All equipment is chosen among certified products that meet anti-static and fire-resistant standards.

Safety Culture, Management Systems, and Personnel Training

Occupational health and safety culture at the facility follows an approach of continual education and awareness instead of depending mainly on punishment and force. Regular toolbox training takes place, and “Risk and Safety Talk” cards are utilized to facilitate the development of employees' increased awareness of their own behavior and dangers related to it. In case of any violations of occupational health and safety guidelines, the facility does not depend only on punishing and authoritarian measures, such as keeping formal records or delivering harsh verbal warning, but instead, employees are motivated by means of guiding questions and constructive communication to identify and understand the risks.

All personnel involved in the operation of dangerous cargo are trained in IMDG Code in terms of labeling, placarding, and awareness by means of organizations approved by the Ministry every two years. Pre-operation briefings are conducted when there is a new chemical substance which has never been handled before.

Near misses, environmental accidents, and small accidents which require first aid are promptly recorded in the incident reporting module of the integrated quality and management system, known as QDMS, by team supervisors concerned. Corrective and preventive actions arising from root cause analysis performed by the Accident Investigation Team are followed up and closed out in QDMS.

Operational Continuity and the Supply Chain

The disruptions to terminal operations can have consequences not only for the terminal but also for maritime and inland shipping activities related to the terminal. For instance, delays in the delivery of hazardous liquids as raw materials in the chemical industry, plastics, and agriculture can cause further logistics disruptions. The safety practices suggested by this study must be viewed not only through the perspective of minimizing risks within the terminal but also through the lens of their possible influence on supply chain continuity.

However, considering that the scale of this case study includes one terminal and only two participants, the extent of economic consequences and their influence on international business have not been quantified. Thus, the evaluation is based on the assumption about the role of safe and uninterrupted terminal operations in achieving supply chain continuity.

In light of the above, it is clear that safety procedures in hazardous cargo handling are important not just from the perspective of occupational health and safety but from a more operational one as well. For instance, problems like fires, explosions, spills, malfunctioning equipment, and the reactions of incompatible chemicals can bring operations involving handling and storing of cargo to a temporary

standstill. Measures taken to prevent these problems therefore play a dual role in ensuring minimal disruption to operations as well.

DISCUSSION

The interviews carried out with two officials responsible for the handling of hazardous liquids at the port, aided by an analysis of the institutions' documents, show that the risk of hazardous material in the terminal is addressed by using regulatory compliance and preventive measures. Technical controls, maintenance, training of the personnel, safety communication, and emergency planning play a significant role in the risk management strategy of the terminal.

The results resonate with the study carried out by Zorba (2009), according to whom safety culture plays a vital role in averting accidents when handling hazardous materials. Daily toolbox meetings and "Risk and Safety Talk" cards are good examples of mechanisms of error discussion instead of punishment only. Such communication-based strategy can also be used to handle human error identified by Mert and Çetinyokuş (2020).

Maintenance and technical activities can be considered another critical element of the safety system in the terminal. Adherence to standards like API 650 and API 653, tank and pipeline inspections, and SAP monitoring show the relevance of equipment management emphasized by Chen et al. (2020). Measures relating to static electricity, pressure, flow rates, and temperature sensitivity of cargo are additional ways to ensure the prevention of dangerous situations.

Also, it can be seen that in the process of operation, training and regulation are included. In contrast to deficiencies in training noted by Ünal and Usluer (2015), workers of the terminal regularly undergo updated IMDG Code training and obtain necessary certification in certified organizations. PPE and compatibility matrices contribute to compliance with safety regulations and prevent incompatible substances from being transported or stored together.

The preparation for emergencies also relies on joint plans involving occupational safety and health, industrial accidents, and marine pollution. Such an organized strategy follows the significance of emergency planning that is emphasized by Kuzu (2021). The internal response team and the tools used for containing spills and accidents (booms, etc.) allow a quick reaction in case of any problems.

In conclusion, the results show that the safety of terminals correlates directly with their operational continuity. Accident prevention measures, maintenance, training, safety communication, and emergency preparedness can help reduce the possibility of accidents and operational interruptions that could influence the delivery of cargo. Consequently, safety management can be treated as a crucial element of continuity within terminal operations and the entire supply chain.

CONCLUSION

The risks, health and safety policies, and emergency response systems relating to hazardous liquid bulk cargo at the terminal were analyzed via the case study. The results of interviews, documents review, and literature review show that risk management in maritime hazardous cargo logistics should not be limited only to regulatory compliance.

The communication and safety culture that is practiced in the personnel management is a good example. Instead of being solely dependent on punishment to the employees who violate the rules and pose risks to their safety, the terminal makes use of communication methods designed to make them aware of the risks of their work. Training sessions, along with the "Risk and Safety Talk" cards, can be mentioned as another way to ensure safety awareness.

As far as physical and operational risks are concerned, adhering to international engineering standards, such as API standards and maintaining maintenance schedules helps in managing equipment risks. Some of the measures that have been employed include minimum flow rates for reducing static electricity, temperature control for reactive cargoes, and compatibility matrices for isolating incompatible chemicals in order to ensure operational safety. Implementation of various emergency plans in coordination is another practice employed by the terminal for managing risks.

Some of the implications of the research findings are presented below. Compatibility matrices, QDMS incident reporting, and communication-based safety culture of the terminal may provide some practices for the risk management at other terminals operating in similar conditions. Taking into account the physical risks related to road tanker traffic around the terminal, it is worth considering the appropriate traffic arrangement and parking areas in cooperation with relevant institutions.

Further research can be done on the topic by conducting comparative case studies on various liquid bulk terminals and using quantitative techniques to determine the impact of disruptions on the continuity of the supply chain. Other research avenues include the analysis of artificial intelligence-based early warning systems and IoT-based monitoring systems in the operations of hazardous cargo terminals.

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MAKİNE ÖĞRENMESİYLE HAT BAZINDA YOLCU SAYISI VE BİRİM GELİR TAHMİNİ: TİCARİ PLANLAMA OPTİMİZASYONU

PASSENGER VOLUME AND UNIT REVENUE FORECASTING AT THE ROUTE LEVEL USING MACHINE LEARNING: COMMERCIAL PLANNING OPTIMIZATION

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ABSTRACT
The aviation industry requires effective commercial planning mechanisms because of rapidly changing demand, intense competition, high operating costs, and limited capacity. Accurate forecasting of passenger demand and unit revenue per passenger is essential for effectively managing flight frequency, aircraft type, seat capacity, and pricing decisions. This study aims to forecast route-level passenger volume and unit revenue using machine learning algorithms and to examine the contribution of these forecasts to airline commercial planning processes. The analysis incorporates historical flight data, seasonality indicators, competitors' airfares, socioeconomic variables, and booking curves representing the development of reservations over time. Multiple linear regression, Random Forest, and deep learning models were developed to forecast passenger volume and unit revenue, and their predictive performances were evaluated comparatively. The findings indicate that machine learning models accounting for nonlinear relationships and complex interactions among variables produce more successful results than traditional statistical methods. The developed models enable more accurate forecasting of route-level demand fluctuations and support improvements in aircraft type allocation, capacity management, and dynamic pricing decisions. Compared with traditional forecasting methods, the machine learning-supported commercial planning approach resulted in a 4.2% increase in passenger load factor and a 5.8% increase in total unit revenue. These improvements demonstrate that route-level forecasts can provide airlines with more flexible and timely commercial decision-making capabilities. In conclusion, machine learning-based forecasting systems constitute a strategic instrument for strengthening airlines' data-driven decision-making capacity, revenue management performance, operational efficiency, and competitiveness. The study also provides a practical framework that airline managers can use when integrating predictive analytics into commercial planning and capacity allocation processes under uncertain market conditions.
Keywords: Machine Learning, Passenger Demand Forecasting, Unit Revenue, Airline Commercial Planning, Dynamic Pricing.

ÖZET
Havacılık sektörü; talepteki hızlı değişimler, yoğun rekabet, yüksek operasyonel maliyetler ve sınırlı kapasite nedeniyle etkili ticari planlama mekanizmalarına ihtiyaç duymaktadır. Yolcu talebinin ve yolcu başına elde edilen birim gelirin doğru tahmin edilmesi; uçuş sıklığı, uçak tipi, koltuk kapasitesi ve fiyatlandırma kararlarının etkin biçimde yönetilebilmesi açısından önem taşımaktadır. Bu çalışmanın amacı, makine öğrenmesi algoritmaları kullanılarak hat bazında yolcu sayısını ve birim geliri tahmin etmek ve elde edilen tahminlerin havayolu ticari planlama süreçlerine katkısını incelemektir. Araştırmada geçmiş dönem uçuş verileri, mevsimsellik göstergeleri, rakip havayollarının fiyatları, sosyoekonomik değişkenler ve rezervasyonların zamana bağlı gelişimini gösteren rezervasyon eğrileri kullanılmıştır. Yolcu sayısı ve birim gelir tahminleri için çoklu doğrusal regresyon, Rastgele Orman ve derin öğrenme modelleri oluşturulmuş; modellerin tahmin performansları karşılaştırmalı olarak değerlendirilmiştir. Bulgular, doğrusal olmayan ilişkileri ve değişkenler arasındaki karmaşık etkileşimleri dikkate alan makine öğrenmesi modellerinin geleneksel istatistiksel yöntemlere göre daha başarılı sonuçlar ürettiğini göstermiştir. Geliştirilen tahmin modellerinin kullanılmasıyla hat bazında talep dalgalanmalarının daha doğru öngörülebildiği; uçak tipi tahsisi, kapasite yönetimi ve dinamik fiyatlandırma kararlarının iyileştirilebildiği belirlenmiştir. Makine öğrenmesi destekli ticari planlama yaklaşımının geleneksel yöntemlere kıyasla yolcu doluluk oranında %4,2, toplam birim gelirde ise %5,8 oranında artış sağladığı tespit edilmiştir. Sonuç olarak çalışma, makine öğrenmesi temelli tahmin

sistemlerinin havayolu işletmelerinin veri odaklı karar alma yeteneğini, gelir yönetimi performansını ve rekabet gücünü geliştirebilecek stratejik bir araç olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Makine Öğrenmesi, Yolcu Talebi Tahmini, Birim Gelir, Havayolu Ticari Planlaması, Dinamik Fiyatlandırma.

EFFECT OF UNDERWATER HULL CLEANING AND PROPELLER POLISHING ON SHIP SPEED-PROPULSION POWER PERFORMANCE: A CASE STUDY

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ABSTRACT
Marine biofouling increases the roughness of underwater hull and propeller surfaces and may consequently increase ship resistance and deteriorate propulsion performance. The aim of this study is to evaluate the effect of combined underwater hull cleaning and propeller polishing on the propulsion performance of an anonymized commercial vessel under real operating conditions. Heavy biofouling was documented by a pre-cleaning underwater inspection, including severe fouling over a substantial part of the flat bottom and extensive fouling on the propeller surfaces. The cleaning intervention was carried out in May 2025. Log Abstract records covering the 60-day periods before and after the intervention were used. Because a reliable measured speed-through-water signal was not available, speed through water was excluded from the analysis and speed over ground (SOG) was used as the speed variable. Current speed and relative current direction were used to derive a longitudinal current component, which was included in the analysis to reduce the influence of current on SOG. The dataset was restricted to directional port-to-port routes available in both periods, Noon sea-passage observations, segments of at least 50 NM, and records with SOG of at least 8 kn. The final dataset consisted of 26 observations, including 15 pre-cleaning and 11 post-cleaning records. After accounting for route, propulsion power, displacement, wind, wave height, and current, the adjusted post-cleaning SOG was estimated to be 8.15% higher at comparable propulsion power. The findings indicate a marked near-term improvement in speed-power performance after the removal of documented heavy biofouling and demonstrate the importance of accounting for environmental and operational conditions when evaluating maintenance effects using real ship operational data.
Keywords: biofouling; underwater hull cleaning; propeller polishing; ship performance; speed-power relationship.

INTRODUCTION
Marine biofouling is the accumulation of microorganisms, algae, plants, and animals on submerged ship surfaces. As fouling develops, the roughness of the underwater hull and propeller increases, raising frictional resistance and potentially deteriorating propulsion performance. A fouled vessel may therefore require more propulsion power to maintain a given speed or may achieve a lower speed at the same power. The International Maritime Organization (IMO) recognizes biofouling management as an important component of ship maintenance and notes that maintaining clean underwater surfaces can support hydrodynamic and energy performance (IMO, 2023). Recent IMO guidance also addresses in-water cleaning as a biofouling-management option while emphasizing the need to manage coating condition and environmental releases associated with cleaning activities (IMO, 2025).
The physical relationship between surface condition and propulsion performance is well established. Schultz (2007) showed that increasing coating roughness and fouling severity can create substantial resistance and powering penalties. Numerical self-propulsion work by Farkas et al. (2020) likewise demonstrated that biofilm can materially increase delivered-power demand and reduce ship speed under the modeled conditions. Because fouling growth depends on time, coating condition, route, and operating profile, the associated performance penalty is not necessarily constant; time-dependent modeling by Uzun et al. (2019) highlights the dynamic character of biofouling-related resistance and powering.
Operational studies provide complementary evidence from ships in service. Adland et al. (2018), using data from eight Aframax tankers, reported measurable energy-efficiency benefits following periodic underwater hull cleaning. Laurie et al. (2021) showed that operational and environmental data can be used to identify fouling-related changes in shaft-power performance, while Gupta et al. (2022) demonstrated the value of in-service data for monitoring performance around hull and propeller cleaning events. More recent interpretable data-driven approaches have also incorporated fouling and weather

effects when predicting shaft power, fuel consumption, and speed (Kim & Roh, 2024), and tree-based models have been used to assess hull and propeller degradation associated with biofouling (Themelis et al., 2024).

A central difficulty in evaluating a cleaning event from operational data is that the pre-cleaning and post-cleaning periods are rarely observed under identical conditions. Speed and power demand vary with loading, route, wind, waves, current, and operating decisions; therefore, a direct comparison of raw averages can misrepresent the maintenance effect. ISO 19030 provides a standardized framework for monitoring changes in hull and propeller performance over time (ISO, 2016a, 2016b). Against this background, this study evaluates whether an anonymized commercial vessel with documented heavy biofouling achieved higher speed at comparable propulsion power following combined underwater hull cleaning and propeller polishing. Major operational and environmental differences were explicitly accounted for in the analysis.

MATERIALS AND METHODS

Case Vessel and Cleaning Intervention

The study was designed as an observational before-and-after case study based on real operational records. The vessel and company are not identified because the underlying operational and maintenance information is commercially confidential. In May 2025, the vessel underwent combined underwater hull cleaning and propeller polishing while remaining in service.

A pre-cleaning underwater inspection provided direct physical evidence of the fouling condition. Heavy fouling was documented over a substantial portion of the flat-bottom area, together with extensive fouling on the propeller surfaces. Following the intervention, the relevant hull surfaces were reported as cleaned and the propeller as polished. These observations were used to confirm that the performance comparison was associated with a documented maintenance event rather than an assumed deterioration in hull condition.

Operational Data and Data Selection

Operational performance was evaluated using the vessel's Log Abstract records. The principal variables used in the analysis were speed over ground (SOG), propulsion power, displacement, wind, wave height, current, and directional port-to-port route information. Propulsion power was used as the primary power variable because it most directly represented the power associated with propulsion in the available operational record.

Although the Log Abstract contained a speed-through-water (STW) field, internal technical verification showed that this field did not represent a reliable measured speed-log signal and, in practice, largely reproduced SOG. STW was therefore excluded rather than treated as a valid measurement. SOG was retained as the speed variable. To reduce the influence of current on SOG, current speed and relative current direction were combined to represent the component of current acting along the vessel's direction of travel. Wind direction and intensity, together with wave height, were also considered in the statistical adjustment.

The primary comparison used the 60-day periods before and after cleaning, with the intervention day excluded. Only Noon sea-passage records were retained. Segments shorter than 50 NM and observations with SOG below 8 kn were excluded to reduce the influence of short passages and maneuvering. In addition, only directional port-to-port routes represented in both the pre-cleaning and post-cleaning periods were used. This filtering produced a final dataset of 26 observations: 15 pre-cleaning and 11 post-cleaning records distributed across six common directional routes.

Table 1. Summary of the study design and analytical dataset

Characteristic	**Value**
Vessel identification	Anonymized commercial vessel
Intervention	Underwater hull cleaning + propeller polishing
Cleaning period	May 2025

Characteristic	Value
Primary comparison window	60 days before and 60 days after cleaning
Included records	Noon sea-passage observations
Minimum segment distance	50 NM
Minimum SOG	8 kn
Primary speed variable	Speed Over Ground (SOG)
Primary power variable	Propulsion Power
Final dataset	26 observations (15 pre-cleaning; 11 post-cleaning)
Common directional routes	6

Statistical Analysis

A multivariable log-linear regression model was used to estimate the post-cleaning change in speed at comparable propulsion power. The dependent variable was the natural logarithm of speed over ground, ln(SOG). The model included a post-cleaning indicator, the natural logarithms of propulsion power and displacement [ln(propulsion power) and ln(displacement)], route fixed effects, and terms representing wind, wave height, and the longitudinal current component. This structure was selected to compare the pre-cleaning and post-cleaning speed–power relationship while accounting for differences in loading, route, and environmental conditions.

The post-cleaning coefficient was converted to a percentage effect using the exponential transformation. Because more than one observation could belong to the same voyage, uncertainty in the primary model was estimated using voyage-clustered standard errors. The main result is therefore reported as the adjusted percentage change in SOG, its 95% confidence interval, and the associated p-value. The analysis was intended to estimate an adjusted operational association around the cleaning event; it was not designed to establish a universal causal effect applicable to other vessels.

Data Confidentiality

The Log Abstract records and underwater inspection information are company operational records and are not publicly available. Only anonymized, aggregated, and derived information required to describe the analysis is reported in this paper.

RESULTS AND DISCUSSION

Operational Comparison and Main Result

The pre-cleaning inspection confirmed a substantial fouling condition, particularly on the flat bottom and propeller surfaces. However, the operating conditions in the two periods were not identical. In the raw data, mean post-cleaning SOG was only modestly higher, while propulsion power and displacement were also higher and the environmental conditions differed. This illustrates why an unadjusted before-and-after comparison would not provide a reliable estimate of the maintenance-associated performance change.

After adjustment for propulsion power, displacement, route, wind, wave height, and current, the post-cleaning SOG was estimated to be 8.15% higher at comparable propulsion power. The voyage-clustered 95% confidence interval was 4.00% to 12.47%, and the result was statistically significant ($p < 0.001$). The adjusted speed-power curves therefore indicate an upward shift in speed performance after cleaning: within a comparable propulsion-power range, the post-cleaning relationship is positioned above the pre-cleaning relationship.

Table 2. Main adjusted speed-power result

Performance indicator	Post-cleaning change	95% confidence interval	p-value
Adjusted SOG at comparable propulsion power	+8.15%	+4.00% to +12.47%	<0.001

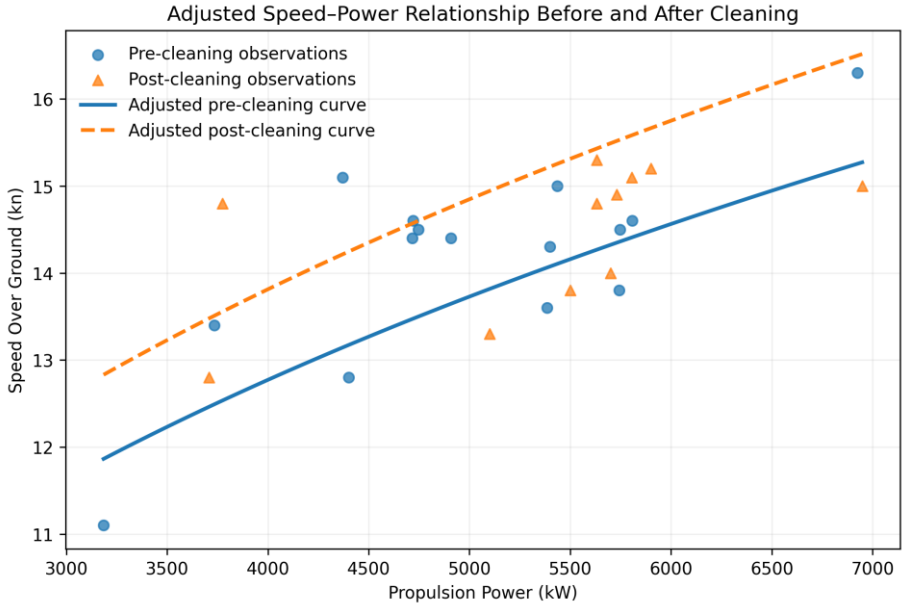


Figure 1. Adjusted speed-power relationship before and after cleaning

Figure 1 illustrates the adjusted speed–power relationships before and after the cleaning intervention. Across the comparable propulsion-power range, the post-cleaning curve remains above the pre-cleaning curve, indicating that the vessel achieved a higher SOG at a given propulsion power after cleaning. The separation between the two curves represents the model-adjusted performance difference after accounting for variations in displacement, route, wind, wave height, and current. This upward shift is consistent with an improvement in propulsion performance following the removal of documented heavy biofouling.

Interpretation in the Context of Previous Studies

The estimated 8.15% change should be interpreted as an adjusted speed difference at comparable propulsion power, not as an 8.15% fuel saving and not as a permanent performance gain. The study concerns one vessel, one combined maintenance event, and a relatively short period around that event. The appropriate interpretation is that the vessel showed a marked near-term improvement in adjusted speed-power performance after the removal of documented heavy biofouling.

The direction of the observed change is consistent with the physical mechanism and with previous literature. Schultz (2007) demonstrated that fouling-related roughness increases resistance and power demand, while Farkas et al. (2020) showed through self-propulsion analysis that biofilm can produce substantial propulsion penalties under modeled conditions. In operational data, Adland et al. (2018) identified energy-efficiency benefits after periodic hull cleaning, and Laurie et al. (2021) detected fouling-related deterioration in shaft-power performance. These studies support the expectation that removing significant fouling can improve propulsion performance, although they do not use identical performance metrics.

The broader operational-data literature also supports the use of in-service records for condition monitoring. Gupta et al. (2022) showed that performance changes around hull and propeller cleaning can be extracted from ship operational data, while Kim and Roh (2024) demonstrated the value of interpretable models that account for fouling and weather effects. Themelis et al. (2024) similarly used tree-based methods to assess hull and propeller degradation. At the same time, the time-dependent

character of biofouling described by Uzun et al. (2019) cautions against treating any cleaning benefit as a fixed long-term percentage. Because the cited studies variously report power penalties, fuel-consumption changes, speed effects, or performance trends, their percentages should not be compared directly with the present fixed-power speed effect. The relevance lies primarily in the consistency of the direction and the physical plausibility of the observed performance response.

LIMITATIONS

The study has four main limitations. First, a reliable measured STW signal was not available, so SOG was used and the effect of current was included statistically; this does not fully substitute for direct STW measurement. Second, the primary dataset contains 26 Noon observations from a single vessel, which limits statistical precision and external generalization. Third, underwater hull cleaning and propeller polishing were carried out as one combined intervention, so their individual contributions cannot be separated. Finally, the study did not include a concurrent untreated control vessel; consequently, unmeasured time-varying factors cannot be ruled out completely.

These limitations are the reason the result is reported as a near-term adjusted performance improvement for the case vessel rather than as a universal cleaning benefit. Future studies would be strengthened by reliable high-frequency STW and shaft-power measurements, a larger number of cleaning events, and control or sister-vessel comparisons.

CONCLUSION AND RECOMMENDATIONS

This study assessed the short-term propulsion-performance change following combined underwater hull cleaning and propeller polishing on an anonymized commercial vessel for which heavy biofouling had been documented before maintenance. A filtered operational dataset was constructed from common directional routes and Noon sea-passage records within 60 days before and after the intervention. After accounting for propulsion power, displacement, route, wind, wave height, and current, the adjusted post-cleaning SOG was estimated to be 8.15% higher at comparable propulsion power (95% CI: 4.00%-12.47%; $p < 0.001$). The result indicates a clear upward shift in the vessel's near-term speed-power performance after cleaning.

The findings support the use of real operational data to evaluate maintenance effectiveness, provided that loading, route, and environmental differences are addressed explicitly. For practical ship-performance assessment, underwater inspection evidence and adjusted speed-power indicators should be considered together rather than relying solely on raw before-and-after averages. The reported percentage should not be generalized directly to other vessels or interpreted as an equivalent fuel-saving percentage.

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INFLUENCE OF CELLULOSE NANOFIBRIL (CNF) AND CELLULOSE NANOCRYSTAL (CNC) COATINGS ON THE SURFACE WETTABILITY OF CORRUGATED CARDBOARD

SELÜLOZ NANOFİBRİL (CNF) VE SELÜLOZ NANOKRİSTAL (CNC) SÜSPANSİYONLARI İLE YAPILAN KAPLAMALARIN OLUKLU MUKAVVA YÜZEY ISLANABİLİRLİĞİNE ETKİSİ

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Abstract
Paper-based materials have been widely used as alternatives to conventional plastic packaging due to their recyclability, biodegradability, renewability, and biocompatibility. Their favourable properties, combined with their versatility for chemical and surface modification, have attracted increasing interest in sustainable packaging applications. Cellulose-based materials, including paper, paperboard, and corrugated cardboard, offer a unique combination of low density, sustainability, biodegradability, recyclability, and cost-effectiveness compared with conventional packaging materials such as glass, aluminium, and plastics. These characteristics make them particularly attractive for environmentally friendly packaging applications. However, the inherent hydrophilicity of cellulose-based materials can limit their performance in applications where resistance to water and moisture is required. Therefore, surface modification using cellulose-based nanomaterials has emerged as a promising approach for improving their functional properties. In this study, the effects of different coating layer configurations using cellulose nanofibril (CNF) and cellulose nanocrystal (CNC) suspensions on the water contact angle and surface wettability of corrugated cardboard were investigated. The highest water contact angle, indicating the greatest degree of hydrophobicity, was measured at 111.4° ± 3.5° for corrugated cardboard coated with a single layer of cellulose nanocrystal suspension derived from waste newspaper. With the exception of the samples coated with newspaper-derived cellulose nanocrystals, all other coated samples exhibited lower water contact angles than the uncoated control sample (74.4^{o} ± 4.1^{o}). Besides, the inherently hydrophilic nature of cellulose nanofibrils and cellulose nanocrystals resulted in a progressive decrease in the water contact angle of corrugated cardboard surfaces as the number of coating layers increased. In conclusion, this study demonstrates the potential of different nanocellulose types as coating materials for enhancing the water-repellent properties of paper-based products. Furthermore, the water resistance of these coatings could potentially be improved further through appropriate surface modification of nanocellulose to impart hydrophobicity.
Keywords: Packaging, corrugated cardboard, cellulose nanofibril, cellulose nanocrystal, water contact angle, hydrophobicity

Özet
Kâğıt esaslı malzemeler; geri dönüştürülebilirlik, biyolojik olarak parçalanabilirlik, yenilenebilirlik ve biyouyumluluk gibi özellikleri nedeniyle geleneksel plastik ambalaj malzemelerine alternatif olarak yaygın şekilde kullanılmaktadır. Bu malzemelerin sahip olduğu avantajlı özellikler ve kimyasal ve yüzey modifikasyonlarına uygunlukları, sürdürülebilir ambalaj uygulamalarında giderek artan bir ilgi görmelerini sağlamıştır. Kâğıt, karton ve oluklu mukavva gibi selüloz esaslı malzemeler; cam, alüminyum ve plastik gibi geleneksel ambalaj malzemeleriyle karşılaştırıldığında düşük yoğunluk, sürdürülebilirlik, biyolojik olarak parçalanabilirlik, geri dönüştürülebilirlik ve maliyet etkinliği gibi özelliklerin benzersiz bir kombinasyonunu sunmaktadır. Bu özellikler, söz konusu malzemeleri çevre dostu ambalaj uygulamaları açısından özellikle cazip hâle getirmektedir. Ancak, selüloz esaslı malzemelerin doğal hidrofilik yapısı, suya ve neme karşı direnç gerektiren uygulamalardaki performanslarını sınırlayabilmektedir. Bu nedenle, selüloz esaslı nanomalzemelerin kullanıldığı yüzey modifikasyonları, bu malzemelerin fonksiyonel özelliklerinin geliştirilmesine yönelik umut verici bir yaklaşım olarak öne çıkmıştır. Bu çalışmada, selüloz nanofibril (CNF) ve selüloz nanokristal (CNC) süspansiyonları kullanılarak oluşturulan farklı kaplama katmanı konfigürasyonlarının, oluklu mukavvanın su temas açısı ve yüzey ıslanabilirliği üzerindeki etkileri araştırılmıştır. En yüksek su temas açısı ve dolayısıyla en yüksek hidrofobiklik derecesi, atık gazete kâğıdından elde edilen selüloz

nanokristal süspansiyonu ile tek katmanlı olarak kaplanan oluklu mukavvada 111,4° ± 3,5° olarak ölçülmüştür. Gazete kâğıdından elde edilen selüloz nanokristalleri ile kaplanan numuneler hariç olmak üzere, diğer tüm kaplanmış numuneler kaplanmamış kontrol numunesine (74,4° ± 4,1°) kıyasla daha düşük su temas açısı değerleri göstermiştir. Ayrıca, selüloz nanofibrillerin ve selüloz nanokristallerin doğal olarak hidrofilik karaktere sahip olması, kaplama katmanı sayısının artmasıyla birlikte oluklu mukavva yüzeylerinin su temas açısında kademeli bir azalmaya neden olmuştur. Sonuç olarak, bu çalışma, farklı nanoselüloz türlerinin kâğıt esaslı ürünlerin su iticilik özelliklerinin geliştirilmesinde kaplama malzemesi olarak kullanılma potansiyelini ortaya koymaktadır. Ayrıca, nanoselüloza hidrofobik özellik kazandırmaya yönelik uygun yüzey modifikasyonları sayesinde bu kaplamaların suya karşı direnç özelliklerinin daha da geliştirilebileceği düşünülmektedir.

Anahtar kelimeler: Ambalaj, oluklu mukavva, selüloz nanofibril, selüloz nanokristal, su temas açısı, hidrofobik

SOURCE-BASED ANALYSIS AND CLASSIFICATION OF PORT-RELATED EMISSIONS

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Abstract
Ports are major transportation hubs where maritime and land-based transportation activities intersect, resulting in the concentration of air pollutants and greenhouse gas emissions from various operational activities. This study aims to classify port-related emissions according to their primary source categories and to determine the contribution of each source to the overall port emissions profile. Accordingly, emission sources are evaluated based on their operational characteristics, including seagoing vessels, domestic vessels, cargo handling equipment, heavy-duty vehicles, locomotives, and the electrical grid.
In the study, port activities are first classified into mobile and stationary emission sources, followed by a specific assessment of sources directly associated with cargo movement. In addition to vessel operations, cargo handling equipment, and landside transportation activities within the port, emissions associated with electricity consumption are also considered. The assessment focuses primarily on key air pollutants and greenhouse gases associated with port operations, including NOx, SOx, PM10, PM2.5, CO, and CO_2.
For the comparison of emission sources, not only total emission quantities but also emissions normalized by operational indicators such as vessel calls, cargo throughput, TEU, equipment activity, and energy consumption are considered. This approach enables different source categories to be compared not only in terms of their absolute emission quantities but also according to their emission intensities per unit of operational activity.
The assessment demonstrates that considering port emissions solely from vessels does not fully represent the overall emission profile of a port. Therefore, the study highlights the importance of a source-specific and operation-oriented approach in the development of effective emission reduction strategies for port operations.
Keywords: Port Emissions; Emission Sources; Cargo Movement; Emission Inventory; Maritime Transportation.

THE RELATIONSHIP BETWEEN RAILWAY ELECTRIFICATION AND FREIGHT TRANSPORT VOLUME: A PANEL DATA ANALYSIS OF EUROPEAN COUNTRIES

DEMİRYOLU TAŞIMACILIĞINDA ELEKTRİFİKASYONUN TAŞIMA HACMİ İLE İLİŞKİSİ: AVRUPA ÜLKELERİ ÜZERİNE BİR PANEL VERİ ANALİZİ

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Abstract
Electrification is an important infrastructure policy in railway transport, particularly for improving energy efficiency and supporting environmental sustainability. However, it remains unclear how greater electrification of the railway network is reflected in the operational characteristics of freight transport and whether it is associated with higher transport intensity. This study empirically examines the relationship between railway electrification and freight train load intensity across European countries over the period 2010–2024. Load intensity is measured as the ratio of freight transported to train-kilometers, thereby capturing the level of freight transport generated per unit of train operation. The analysis employs a two-way fixed-effects model that accounts for differences across countries and years. The study is based on a total of 434 country-year observations from 30 European countries with sufficient data for the core variables. The findings indicate that changes in the electrification rate are not statistically significantly associated with changes in freight train load intensity. Although the estimated coefficient on electrification is positive, it is statistically insignificant ($\beta = 0.0011$; $p = 0.747$). This result indicates that a higher share of electrified railway lines, by itself, does not lead freight trains to operate with heavier loads. Accordingly, no systematic relationship is identified between higher levels of railway electrification and greater freight transport volume. The main finding remains consistent in robustness analyses using alternative standard error estimation methods and a narrower country sample with complete data. The study demonstrates that the relationship between railway electrification and freight transport performance should not be assessed on the basis of a single infrastructure indicator. Instead, a more comprehensive assessment that considers the varying infrastructure, demand, and operational conditions under which freight rail systems operate is warranted.
Keywords: Railway transport, railway electrification, panel data analysis, fixed-effects model, European countries

Özet
Demiryolu taşımacılığında elektrifikasyon, enerji verimliliğinin artırılması ve çevresel sürdürülebilirliğin desteklenmesi açısından önemli bir altyapı politikasıdır. Bununla birlikte, demiryolu ağının elektriklendirilme düzeyindeki artışın yük taşımacılığının operasyonel yapısına nasıl yansıdığı ve daha yüksek bir taşımacılık yoğunluğu ile ilişkili olup olmadığı yeterince açık değildir. Bu çalışma, Avrupa ülkelerinde demiryolu elektrifikasyon oranı ile yük trenlerinin yük yoğunluğu arasındaki ilişkiyi 2010–2024 dönemi için ampirik olarak incelemektedir. Çalışmada yük yoğunluğu, taşınan yük miktarının tren-kilometreye oranı kullanılarak ölçülmüş ve böylece yük trenlerinin birim işletim başına gerçekleştirdiği taşıma düzeyi değerlendirilmiştir. Analizde, ülkeler ve yıllar arasındaki farklılıkları birlikte dikkate alan iki yönlü sabit etkiler modeli kullanılmıştır. Araştırma, temel değişkenlerde yeterli veri bulunan 30 Avrupa ülkesine ait toplam 434 ülke-yıl gözlemine dayanmaktadır. Bulgular, elektrifikasyon oranındaki değişim ile yük yoğunluğundaki değişim arasında istatistiksel olarak anlamlı bir ilişki bulunmadığını ortaya koymaktadır. Elektrifikasyon katsayısı pozitif olmakla birlikte istatistiksel olarak anlamsızdır ($\beta = 0{,}0011$; $p = 0{,}747$). Bu sonuç, demiryolu ağındaki elektrifikasyon oranının artmasının tek başına yük trenlerinin daha yoğun yük taşımasını sağlamadığını göstermektedir. Dolayısıyla, elektrifikasyon düzeyindeki artışın yük taşımacılığındaki hacmi otomatik olarak artırdığı yönünde bir ilişki tespit edilmemiştir. Temel bulgu, farklı standart hata hesaplama yöntemleri ve tam veri içeren daha dar ülke örneklemi kullanılarak gerçekleştirilen sağlamlık analizlerinde de korunmaktadır.

Çalışma, demiryolu elektrifikasyonu ile yük taşımacılığı performansı arasındaki ilişkinin tek bir altyapı göstergesi üzerinden değerlendirilmemesi gerektiğini; farklı altyapı, talep ve operasyonel koşulların birlikte ele alınmasının daha sağlıklı bir değerlendirme sağlayacağını ortaya koymaktadır.
Anahtar kelimeler: Demiryolu taşımacılığı, demiryolu elektrifikasyonu, panel veri analizi, sabit etkiler modeli, Avrupa ülkeleri

THE IMPORTANCE AND SUSTAINABILITY OF WETLANDS: THE CASE OF MILLEYHA WETLAND

SULAK ALANLARIN ÖNEMİ VE SÜRDÜRÜLEBİLİRLİĞİ: MİLLEYHA SULAK ALANI ÖRNEĞİ

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Abstract
Wetlands are important natural landscapes that provide essential ecosystem functions, including biodiversity conservation, water regime regulation, flood prevention, water purification, and carbon cycling, as well as recreational, educational, and cultural values. However, anthropogenic pressures such as urbanization, agricultural activities, construction, and waste threaten the ecological integrity of wetlands and the continuity of the ecosystem services they provide. This study evaluates the ecological importance and sustainability of wetlands through the case of the Milleyha Wetland. Located in Samandağ, Hatay, Milleyha is an ecologically significant landscape due to the coexistence of wetland, reedbed, dune, and coastal habitats, its rich biodiversity, and its location along the Eastern Mediterranean bird migration route. Previous studies have identified 183 vascular plant taxa and 76 typical halophytes in the area; however, agricultural activities, waste disposal, and construction have also been identified as major pressures on the site. The designation of Milleyha as a wetland in 2021 and its recognition as a natural protected area in 2025 represent important steps toward its conservation. Nevertheless, ensuring the sustainability of wetlands cannot be achieved through legal protection status alone. The conservation of the ecological character of wetlands and the continuity of the ecosystem services they provide require conservation decisions to be supported by spatial planning, integrated site management, monitoring, and stakeholder participation. Accordingly, the sustainability of Milleyha depends on directing land-use decisions in its surroundings in accordance with ecological sensitivities, maintaining habitat integrity and ecological connectivity, and addressing the area through an integrated landscape planning and management approach.

Keywords: Wetland, Milleyha, ecosystem services, biodiversity, sustainability, landscape planning, wetland management.

Özet
Sulak alanlar biyolojik çeşitliliğin korunması, su rejiminin düzenlenmesi, taşkınların önlenmesi, suyun arıtılması ve karbon döngüsünün sürdürülmesi gibi temel ekosistem işlevlerinin yanı sıra rekreasyon, eğitim ve kültürel değerleriyle önemli doğal peyzajlardır. Ancak kentleşme, tarımsal faaliyetler, yapılaşma ve atıklar gibi antropojenik baskılar sulak alanların ekolojik bütünlüğünü ve sundukları ekosistem hizmetlerinin sürekliliğini tehdit etmektedir. Bu çalışma sulak alanların ekosistem açısından önemini ve sürdürülebilirliğini Milleyha Sulak Alanı örneği üzerinden değerlendirmektedir. Hatay'ın Samandağ ilçesinde yer alan Milleyha; sulak alan, sazlık, kumul ve kıyı habitatlarını bir arada barındırması sahip olduğu biyolojik çeşitlilik ve Doğu Akdeniz kuş göç yolu üzerindeki konumu nedeniyle ekolojik açıdan önemli bir peyzajdır. Literatürde alanda 183 damarlı bitki taksonu ve 76 tipik halofit belirlenmiştir fakat aynı zamanda alanda tarımsal kullanım, atık dökümü ve yapılaşmanın alan üzerinde baskı oluşturduğu ortaya konulmuştur. Alanın 2021 yılında sulak alan olarak ilan edilmesi ve 2025 yılında doğal sit statüsü kazanması koruma açısından önemli adımlar olmakla birlikte sulak alanların sürdürülebilirliğinin yalnızca koruma statüsüyle sağlanamayacağı açıktır. Sulak alanların ekolojik karakterinin ve sunduğu hizmetlerin sürdürülebilmesi için koruma kararlarının mekânsal planlama, bütünleşik alan yönetimi izleme ve paydaş katılımı ile desteklenmesi gerekmektedir. Bu doğrultuda Milleyha'nın sürdürülebilirliği çevresindeki arazi kullanım kararlarının ekolojik hassasiyetler doğrultusunda yönlendirilmesi, habitat bütünlüğü ve ekolojik bağlantılılığın korunması ve alanın bütüncül peyzaj planlama ve yönetim yaklaşımıyla ele alınmasına bağlıdır.
Anahtar Kelimeler: Sulak alan, Milleyha, ekosistem hizmetleri, biyolojik çeşitlilik, sürdürülebilirlik, peyzaj planlama, sulak alan yönetimi.

SYNTHESIS AND CHARACTERIZATION OF AROMATIC DIHYDROXY COMPOUNDS CONTAINING AN IMINE BOND AND THEIR ALIPHATIC AND AROMATIC POLY(AZOMETHINE-URETHANES)

İMİN BAĞI İÇEREN AROMATİK DİHİDROKSİ BİLEŞİKLERİ VE ONLARIN ALİFATİK VE AROMATİK POLİ(AZOMETİN-ÜRETAN)LARININ SENTEZİ VE KARAKTERİZASYONU

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Abstract
Oligomers or polymers containing a conjugated π system in their structure are used in many industrial applications due to their semiconducting properties. An alternative to polymers with a conjugated π bond structure could be oligo- and poly(azomethine)s which contain an azomethine unit (-HC=N-) in their main backbone or Schiff base-based polymers. Schiff base compounds are obtained in high yields and with high purity as a result of the condensation reaction of diamines with dialdehydes or diketones. Oligo or poly(azomethines) have been studied by many researchers in recent years. In general, aromatic compounds containing a dihydroxy group react with isocyanates to form imine-based polyurethane compounds [1, 2]. These types of oligo or poly(azomethine-urethane) compounds are used in many industrial applications because their structures contain both phenyl groups and various other functional groups. Since the phenyl units in the main chain impart rigidity to the structure, this imine based poly(urethane) compounds exhibit excellent thermal stability [2].
Schiff base compounds were obtained from the condensation reaction of terephthalaldehyde with 2-aminophenol, 4-aminophenol, 2-amino-5-nitrophenol, and 4-amino-3-methylphenol in an alcoholic medium. The resulting Schiff base compounds were converted into poly(azomethine urethanes) through reactions with 1,6-diisocyanatehexane, methylene di-p-phenyl diisocyanate, 4,4′-methylbis(cyclohexyl isocyanate), and isophorone diisocyanates [2].
The structures of the synthesized Schiff bases and poly(azomethine-urethane) compounds were confirmed by FT-IR, UV-Vis, ^{1}H-NMR, and ^{13}C-NMR measurements. The thermal properties of the Schiff bases and poly(azomethine-urethane) compounds were determined using TGA-DTA and DSC techniques. The surface morphologies of the poly(azomethine-urethanes) were determined by SEM analysis. The electrochemical and optical bandgap values of all compounds were determined from CV and UV-Vis measurements, respectively. The photoluminescence properties of the synthesized compounds were determined from spectrofluorometric measurements of their solutions in DMF. The number-average molecular weight (Mn), weight-average molecular weight (Mw), and polydispersity index (PDI) values of the synthesized poly(azomethine-urethane) compounds were determined by gel permeation chromatography.
Keywords: Poly(azomethine-urethane), optical band gap, fluorescence, and thermal properties.

Özet
Yapısında konjuge π sistemi bulunan oligomerler veya polimerler yarı iletkenlik özelliklerinden dolayı birçok endüstriyel alanda kullanılmaktadırlar. Konjuge π bağ yapısına sahip polimerlere bir alternatif ana iskeletinde azometin birimi (-HC=N-) içeren oligo-poli(azometin)ler veya Schiff bazlı polimerler olabilir. Diaminlerin dialdehitler veya diketonlarla kondenzasyon tepkimesi sonucu Schiff bazı bileşikleri yüksek verim ve saflıkta elde edilmektedir. Oligo veya poli(azometin)ler son yıllarda birçok araştırmacı tarafından çalışılmaktadır. Genel olarak yapısında dihidroksi grubu içeren aromatik yapılı bileşikler izosiyanatlarla tepkimeye girerek imin yapılı poli üretan bileşiklerine dönüştürülmektedir [1, 2]. Bu tip oligo veya poli(azometin-üretan) bileşikleri yapılarında hem fenil hem de farklı fonksiyonel

gruplar içermeleri nedeniyle endüstride birçok alanda kullanılmaktadır. Ana zincirdeki fenil birimleri yapıya sertlik kazandırdığından, bu tip imin yapılı poli üretan bileşiklerinin termal kararlılıkları oldukça iyidir [2].

Schiff bazı bileşikleri, Tereftaldehit ile 2-amino fenol, 4-amino fenol, 2-amino-5-nitro-fenol, 4-amino-3-metil fenol bileşiklerinin alkol ortamında kondenzasyon reaksiyonundan elde edildi. Elde edilen Schiff bazı bileşikleri 1,6-diizosiyonathekzan, metilen di-p-fenil diizosiyanat, 4,4′-Metilbis(siklohekzil isosiyanat), izoforon diizosiyanatlar ile tepkimesi sonucunda poli(azometin-üretan)lara dönüştürüldü [2].

Sentezlenen Schiff bazlarının ve poli(azometin-üretan) bileşiklerinin yapıları FT-IR, UV-Vis, ^{1}H-NMR, ^{13}C-NMR ölçümleri ile doğrulandı. Schiff bazlarının ve poli(azometin-üretan) bileşiklerinin termal özellikleri TGA-DTA ve DSC teknikleriyle belirlendi. poli(azometin-üretan)ların yüzey morfolojileri SEM ölçümleri ile belirlendi. Tüm bileşiklerin elektrokimyasal ve optik bant boşlukları değerleri sırasıyla CV ve UV-Vis ölçümlerinden belirlendi. Sentezlenen bileşiklerin fotolüminesans özellikleri, DMF'de çözelti formlarındaki spektroflorofotometre ölçümlerinden belirlendi. Sentezlenen poli(azometin-üretan) bileşiklerin sayı- ortalama molekül ağırlığı (Mn), ağırlık ortalama molekül ağırlığı (Mw) ve polidispersite indeksi (PDI) değerleri jel geçirgenlik kromatografisi ile belirlendi.

Anahtar Kelimeler: Poli(azometin-üretan), optik bant aralığı, floresans ve termal özellikler.

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EFFECT OF ANNEALING TEMPERATURE ON THE STRUCTURAL AND OPTICAL PROPERTIES OF ZNO NANOPARTICLES GREEN-SYNTHESİZED USING OKRA EXTRACT

TAVLAMA SICAKLIĞININ OKRA EKSTRAKTI İLE YEŞİL SENTEZLENEN ZNO NANOPARTİKÜLLERİNİN YAPISAL VE OPTİK ÖZELLİKLERİNE ETKİSİ

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Abstract
In this study, zinc oxide (ZnO) nanoparticles were synthesized through a green synthesis approach using okra (*Abelmoschus esculentus*) fruit extract, and the effects of annealing (calcination) temperature on the structural, optical, and morphological properties of the obtained nanoparticles were investigated. The green synthesis approach was employed to prepare ZnO nanoparticles using a plant-derived extract and to comparatively evaluate the influence of different calcination temperatures on the material properties.
The precipitated samples obtained after the synthesis process were separately calcined at 400 °C, 500 °C, and 600 °C in order to determine the effect of annealing temperature. Accordingly, three groups of ZnO nanoparticle samples were prepared under different thermal treatment conditions. Following calcination, the samples were characterized using different analytical techniques to determine their structural, optical, and morphological properties. X-ray diffraction (XRD) analysis was performed to evaluate the crystal structure and crystallinity of the samples. UV-Visible spectroscopy (UV-Vis) was used to investigate their optical properties and light absorption behavior. In addition, scanning electron microscopy (SEM) analyses were carried out to examine the surface morphology, particle appearance, and morphological changes associated with different calcination temperatures.
The characterization results indicate that calcination temperature is an important processing parameter affecting the fundamental material properties of ZnO nanoparticles produced through the green synthesis route. Comparative evaluation of the samples prepared at different temperatures enabled the effects of annealing conditions on the structural, optical, and morphological properties of ZnO nanoparticles to be assessed together. This study aims to comparatively reveal the properties of ZnO nanoparticles obtained at different calcination temperatures and to contribute to the determination of suitable annealing conditions for their potential application areas.
Keywords: Green synthesis, ZnO nanoparticle, okra extract, annealing temperature, characterization

Özet
Bu çalışmada, okra (*Abelmoschus esculentus*) meyve ekstraktı kullanılarak yeşil sentez yöntemiyle çinko oksit (ZnO) nanopartikülleri üretilmiş ve tavlama (kalsinasyon) sıcaklığının elde edilen nanopartiküllerin yapısal, optik ve morfolojik özellikleri üzerindeki etkisi incelenmiştir. Çalışmada yeşil sentez yaklaşımının tercih edilmesiyle, bitkisel kaynaklı bir ekstrakt kullanılarak ZnO nanopartiküllerinin hazırlanması ve farklı kalsinasyon sıcaklıklarının malzeme özellikleri üzerindeki etkilerinin karşılaştırmalı olarak değerlendirilmesi amaçlanmıştır.

Sentez işlemi sonucunda elde edilen çökelti numuneleri, tavlama sıcaklığının etkisini belirleyebilmek amacıyla 400 °C, 500 °C ve 600 °C olmak üzere üç farklı sıcaklıkta ayrı ayrı kalsine edilmiştir. Böylece farklı tavlama koşullarında hazırlanan üç ZnO nanopartikül grubu elde edilmiştir. Kalsinasyon sonrasında elde edilen numuneler, yapısal, optik ve morfolojik özelliklerinin belirlenmesi amacıyla farklı karakterizasyon yöntemleri kullanılarak incelenmiştir. Numunelerin kristal yapı ve kristalinite özelliklerinin değerlendirilmesi için X-ışını difraksiyonu (XRD) analizi gerçekleştirilmiştir. Optik özelliklerin ve ışık soğurma davranışlarının incelenmesi amacıyla UV-Görünür bölge spektroskopisi (UV-Vis) kullanılmıştır. Ayrıca nanopartiküllerin yüzey morfolojilerinin, tanecik görünümlerinin ve farklı kalsinasyon sıcaklıklarına bağlı olarak ortaya çıkan morfolojik değişimlerin değerlendirilmesi için taramalı elektron mikroskobu (SEM) analizleri yapılmıştır.
Elde edilen karakterizasyon verileri, kalsinasyon sıcaklığının yeşil sentez yoluyla üretilen ZnO nanopartiküllerinin temel malzeme özelliklerinin değişiminde etkili bir işlem parametresi olduğunu göstermektedir. Farklı sıcaklıklarda hazırlanan numunelerin karşılaştırılması, tavlama koşullarının ZnO nanopartiküllerinin yapısal, optik ve morfolojik özellikleri üzerindeki etkisinin birlikte değerlendirilmesine olanak sağlamıştır. Bu çalışma ile farklı kalsinasyon sıcaklıklarında elde edilen ZnO nanopartiküllerinin özelliklerinin karşılaştırmalı olarak ortaya konulması ve uygulama alanlarına yönelik uygun tavlama koşullarının belirlenmesine katkı sağlanması amaçlanmaktadır.
Anahtar Kelimeler: Yeşil sentez, ZnO nanopartikül, okra ekstraktı, tavlama sıcaklığı, karakterizasyon

1. INTRODUCTION

Zinc oxide (ZnO) is a II–VI semiconductor that crystallizes in the hexagonal wurtzite structure and combines a wide direct band gap of about 3.37 eV with a large exciton binding energy of approximately 60 meV at room temperature (Özgür et al., 2005; Klingshirn, 2007; Janotti and Van de Walle, 2009). Together with its chemical and thermal stability, low toxicity, and low cost, these characteristics have made ZnO a versatile material for ultraviolet optoelectronics, gas and biological sensors, photocatalysis, and biomedical applications (Özgür et al., 2005; Prasad et al., 2019; Selim et al., 2025). When the particle size is reduced to the nanoscale, the large surface-to-volume ratio and the enhanced surface reactivity further modify its optical, catalytic, and antibacterial behavior (Prasad et al., 2019; Selim et al., 2025).

ZnO nanoparticles can be produced by numerous physical and chemical routes, such as sol–gel, hydrothermal, precipitation, sonochemical, and microwave-assisted methods. These routes frequently require hazardous reagents, elevated temperature and pressure, or expensive equipment, which raises both the cost and the environmental burden of the process (Prasad et al., 2019; Selim et al., 2025; Jadoun et al., 2021). Green synthesis using plant extracts has therefore attracted considerable attention as a simple, low-cost, and environmentally benign alternative (Jadoun et al., 2021; Huang et al., 2021; Agarwal et al., 2017). In this approach, phytochemicals such as flavonoids, phenolic compounds, polysaccharides, and proteins act as reducing, complexing, and capping agents, so that no additional toxic reducing agents or surfactants are needed (Selim et al., 2025; Jadoun et al., 2021; Huang et al., 2021; Agarwal et al., 2017). The characteristics of the resulting nanoparticles depend on the plant source and on synthesis parameters such as the pH, precursor concentration, reaction time, and calcination temperature (Agarwal et al., 2017; Karam and Abdulrahman, 2022).

Okra (Abelmoschus esculentus) is an attractive bio-resource for this purpose because it is renewable, inexpensive, and biodegradable, and its mucilage contains proteins, carbohydrates, polysaccharides, polyphenols, and flavonol derivatives (Prasad et al., 2019). Prasad et al. prepared hexagonal wurtzite ZnO nanoparticles with average sizes of 29–70 nm using okra mucilage and demonstrated their selective photocatalytic degradation of cationic dyes (Prasad et al., 2019). More recently, Selim et al. obtained mainly hexagonal ZnO nanoparticles of 20–27 nm from okra fruit extract after calcination at 500 °C and reported their anticancer and antibacterial activities (Selim et al., 2025). These studies confirm that okra is a suitable medium for ZnO synthesis; however, they were carried out at a single thermal-treatment condition and concentrated mainly on biological or photocatalytic performance. To the best of our knowledge, a systematic comparison of how the calcination temperature influences the structural, morphological, and optical properties of ZnO nanoparticles obtained from okra fruit extract is still limited.

The calcination (annealing) step is decisive in green synthesis, because it decomposes the hydroxide- and organic-containing precursor into ZnO, removes residual organic species originating from the

extract, and governs crystallinity, grain growth, and defect concentration. For ZnO nanoparticles prepared with thyme leaf extract and calcined between 150 and 450 °C, both the FESEM particle size and the XRD crystallite size increased with temperature, while the optical band gap decreased (Karam and Abdulrahman, 2022). Likewise, for ZnO nanoparticles prepared by chemical precipitation and calcined between 400 and 600 °C, the crystallite size increased and the band gap decreased from 3.15 to 3.05 eV (Sharma et al., 2023). These reports indicate that the annealing temperature is a powerful tool for tuning the properties of ZnO nanoparticles, but the optimum condition depends on the precursor system and on the target application.

In the present work, ZnO nanoparticles were synthesized using okra fruit extract and calcined at 400, 500, and 600 °C. The crystal structure, phase purity, and crystallinity of the samples were investigated by X-ray diffraction (XRD), including the crystallite size, lattice parameters, dislocation density, and microstrain; the morphology and particle size were examined by scanning electron microscopy (SEM); and the optical absorption and band gap energy were evaluated by UV–Vis spectroscopy. The aim is to demonstrate that the annealing temperature is a critical parameter for controlling the physical and chemical properties of green-synthesized ZnO nanoparticles and to contribute to the optimization of the temperature for targeted applications.

2. EXPERIMENTAL

2.1 Materials

Zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$, ≥99%), sodium hydroxide (NaOH, ≥98%), and ethanol (96%) were of analytical grade and were used as received without further purification. Fresh okra (*Abelmoschus esculentus*) fruits were obtained from a local market. Deionized (DI) water was used throughout all experiments.

2.2 Preparation of okra fruit extract

Fresh okra fruits were thoroughly washed with tap water and then with DI water to remove dust and surface contaminants. The washed fruits were cut into small slices of about 0.5 cm, and 20 g of the slices was added to 200 mL of DI water in a beaker. The mixture was heated at 70 °C for 30 min under continuous magnetic stirring and then allowed to cool to room temperature. The resulting mucilaginous solution was filtered first through a fine mesh and then through Whatman No. 1 filter paper to obtain a clear light-yellow extract. The extract was stored at 4 °C and used within 24 h to avoid degradation of the bioactive constituents. The polysaccharides, flavonoids, phenolic compounds, and proteins present in the extract were expected to act as reducing, complexing, and capping/stabilizing agents during the formation of the nanoparticles.

2.3 Green synthesis of ZnO nanoparticles

In a typical synthesis, 2.195 g of zinc acetate dihydrate (0.1 M) was dissolved in 100 mL of DI water under vigorous magnetic stirring at room temperature for 15 min. Subsequently, 50 mL of the okra extract was added dropwise to the zinc precursor solution, and the mixture was heated to 60 °C and stirred for 30 min. The pH of the solution was then adjusted to approximately 10 by the dropwise addition of 1 M NaOH solution, upon which a white precipitate formed immediately. The suspension was further stirred at 60 °C for 2 h and aged at room temperature for 12 h. The precipitate was collected by centrifugation at 6000 rpm for 10 min, washed three times with DI water and once with ethanol to remove unreacted ions and loosely bound organic residues, and dried in an oven at 80 °C for 12 h. The dried product was ground in an agate mortar to obtain a fine white powder (the precursor precipitate).

2.4 Calcination (annealing) process

The dried precursor powder was divided into three equal portions, which were placed in alumina crucibles and calcined in a muffle furnace under static air atmosphere at 400, 500, and 600 °C, respectively. The heating rate was 5 °C/min, and the samples were held at the target temperature for 2 h, after which the furnace was allowed to cool naturally to room temperature. The calcination step converts the hydroxide/acetate-containing precursor into crystalline ZnO and removes the organic residues originating from the plant extract. The resulting samples are denoted as ZnO-400, ZnO-500, and ZnO-600 according to the calcination temperature. All other synthesis parameters (precursor

concentration, extract volume, pH, reaction time, and calcination duration) were kept constant so that the annealing temperature was the only variable.

2.5 Characterization techniques

The crystal structure and phase purity of the samples were examined by X-ray diffraction (XRD) using a powder diffractometer with Cu Kα radiation (λ = 1.5406 Å) operated at 40 kV and 30 mA. The patterns were recorded in the 2θ range of 20°–80° with a step size of 0.02° and a scan rate of 2°/min at room temperature. The diffraction peaks were indexed with reference to the standard ZnO card (PDF 36-1451). The crystallite size, lattice parameters, unit-cell volume, dislocation density, and microstrain were calculated from the XRD data using the Debye–Scherrer relation and the related equations given in Section 3.1.

The surface morphology and particle size of the powders were investigated by scanning electron microscopy (SEM). The samples were mounted on carbon tape, sputter-coated with a thin conductive layer (Au) to prevent charging, and imaged at an accelerating voltage of 5–15 kV. The average particle size was determined from the SEM micrographs by measuring at least 100 particles for each sample using ImageJ software.

The optical properties were studied by UV–Vis absorption spectroscopy. For each sample, 1 mg of the powder was dispersed in 10 mL of ethanol and ultrasonicated for 15 min to obtain a homogeneous suspension, and the absorption spectra were recorded in the wavelength range of 200–800 nm using a double-beam spectrophotometer with quartz cuvettes (1 cm path length), using pure ethanol as the reference. The optical band gap energies were determined from the Tauc plots ($(\alpha hv)^2$ versus hv) assuming a direct allowed transition, as described in Section 3.3.

3. RESULTS AND DISCUSSION

3.1 X-ray diffraction (XRD) analysis

Figure 1 shows the XRD patterns of the ZnO nanoparticles synthesized using okra fruit extract and calcined at 400, 500, and 600 °C, together with the standard ZnO reference pattern (PDF 36-1451). All samples exhibit sharp and well-defined reflections in the 2θ range of 20°–80°. The diffraction peaks located at approximately 32.2°, 35.1°, 37.1°, 47.6°, 56.4°, 62.3°, 67.4°, 68.5°, 72.1°, and 77.3° are assigned to the (100), (002), (101), (102), (110), (103), (112), (201), (004), and (202) planes, respectively, while a very weak reflection at approximately 66.1° corresponds to the (200) plane. The peak positions and the relative peak intensities are in good agreement with the reference card (Table 1), confirming the formation of the hexagonal wurtzite structure of ZnO (space group $P6_3mc$) at all annealing temperatures. No additional reflections related to $Zn(OH)_2$, $ZnCO_3$, or other secondary phases were observed, indicating that the precipitate obtained with the phytochemical-assisted route was completely converted to phase-pure ZnO even at 400 °C and that the organic residues originating from the okra extract were removed during calcination.

Table 1. Indexed XRD reflections of the ZnO nanoparticles (2θ and *d*-spacing) and their relative intensities (I/I_0) for samples calcined at 400, 500, and 600 °C, compared with PDF 36-1451.

(*hkl*)	2θ (°)	*d* (Å)	I/I_0 (%) 400 °C	I/I_0 (%) 500 °C	I/I_0 (%) 600 °C	I/I_0 (%) PDF 36-1451
(100)	32.2	2.778	57	64	66	57
(002)	35.1	2.555	44	48	50	44
(101)	37.1	2.421	100	100	100	100
(102)	47.6	1.909	30	31	29	23
(110)	56.4	1.630	41	43	40	32
(103)	62.3	1.489	32	33	31	29
(112)	67.4	1.388	26	27	33	23

Although the phase composition remained unchanged, the annealing temperature strongly affected the intensity and width of the reflections. With increasing temperature from 400 °C to 600 °C, the peak

intensities increased markedly and the peaks became narrower. The height of the dominant (101) reflection at $2\theta \approx 37.1°$ increased progressively in the order 400 °C < 500 °C < 600 °C, and the (100) and (002) reflections at ≈32.2° and ≈35.1° followed the same trend. The full width at half maximum (FWHM) of the (101) peak decreased from 0.45° at 400 °C to 0.38° at 500 °C and 0.30° at 600 °C. This behavior indicates enhanced crystallinity, which is attributed to thermally activated atomic diffusion, the elimination of lattice defects, and the coalescence of small crystallites at elevated temperatures. In addition, the low-intensity high-angle reflections, namely (004) at ≈72.1° and (202) at ≈77.3°, as well as the (112)/(201) doublet at ≈67.4°/68.5°, are barely discernible in the 400 °C sample but become clearly resolved at 600 °C, reflecting improved long-range atomic order. The intensity ratios of the (100), (002), and (101) reflections are close to those of the standard pattern, with (101) being the strongest peak, which shows that annealing does not induce a pronounced preferred orientation.

The average crystallite size (D) was estimated from the FWHM of the (101) reflection using the Debye–Scherrer equation:

$$D = K\lambda / (\beta \cos \theta) \quad (1)$$

where K is the shape factor (0.9), λ is the X-ray wavelength (1.5406 Å for Cu Kα), β is the FWHM in radians, and θ is the Bragg angle. The lattice parameters of the hexagonal cell were calculated from the (100) and (002) reflections using

$$a = 2d_{100} / \sqrt{3}, \quad c = 2d_{002} \quad (2)$$

$$V = (\sqrt{3}/2)\, a^2 c \quad (3)$$

The dislocation density (δ) and the microstrain (ε) were obtained from

$$\delta = 1 / D^2 \quad (4)$$

$$\varepsilon = \beta / (4 \tan \theta) \quad (5)$$

The calculated structural parameters are summarized in Table 2. The crystallite size increased from 18.6 nm at 400 °C to 22.1 nm at 500 °C and 27.9 nm at 600 °C, i.e., by approximately 50% over the investigated temperature range. This is in line with the general trend reported for ZnO nanoparticles obtained by plant-extract-mediated routes, where higher calcination temperatures promote grain growth through the merging of neighboring nanocrystals and a reduction in the total surface energy (Ostwald-ripening-type coarsening) (Karam and Abdulrahman, 2022). Correspondingly, the dislocation density decreased from 2.88×10^{-3} nm^{-2} to 1.28×10^{-3} nm^{-2} and the microstrain decreased from 5.85×10^{-3} to 3.90×10^{-3}, which points to the progressive relaxation of lattice defects, such as oxygen vacancies and zinc interstitials, as well as the removal of residual organic species and hydroxyl groups from the crystal surface. The values obtained from the Scherrer equation should be regarded as lower-bound estimates, because instrumental broadening was not subtracted.

Table 2. Structural parameters of ZnO nanoparticles calcined at different temperatures: FWHM of the (101) peak, crystallite size (D), lattice parameters (a, c), c/a ratio, unit-cell volume (V), dislocation density (δ), and microstrain (ε).

Sample	FWHM (°)	D (nm)	a (Å)	c (Å)	c/a	V (Å^3)	δ (×10^{-3} nm^{-2})	ε (×10^{-3})
400 °C	0.45	18.6	3.207	5.109	1.593	45.5	2.88	5.85
500 °C	0.38	22.1	3.207	5.109	1.593	45.5	2.05	4.94
600 °C	0.30	27.9	3.207	5.109	1.593	45.5	1.28	3.90
PDF 36-1451	–	–	3.250	5.207	1.602	47.6	–	–

The lattice parameters ($a \approx 3.207$ Å and $c \approx 5.109$ Å) and the unit-cell volume (≈45.5 Å^3) did not change appreciably with the annealing temperature, indicating that the wurtzite lattice is stable over the investigated range. The values are slightly lower than those of bulk ZnO (a = 3.250 Å, c = 5.207 Å, V = 47.6 Å^3), while the c/a ratio of about 1.593 is close to the ideal value of 1.633 for a hexagonal close-packed structure and to the standard value of 1.602. Such a small lattice contraction is commonly reported for ZnO nanocrystals and is ascribed to surface-related effects and residual lattice strain in the small crystallites.

Overall, the XRD results demonstrate that annealing temperature is a decisive parameter for the crystallinity of green-synthesized ZnO nanoparticles: increasing the temperature from 400 °C to 600 °C yields larger, better-ordered crystallites with fewer structural defects while retaining the phase-pure wurtzite structure. The improved crystallinity and the reduced defect density at higher temperatures are expected to influence the optical behavior discussed in the following section, since crystallite size and defect concentration are closely related to the band-gap energy and to the defect-related absorption features.

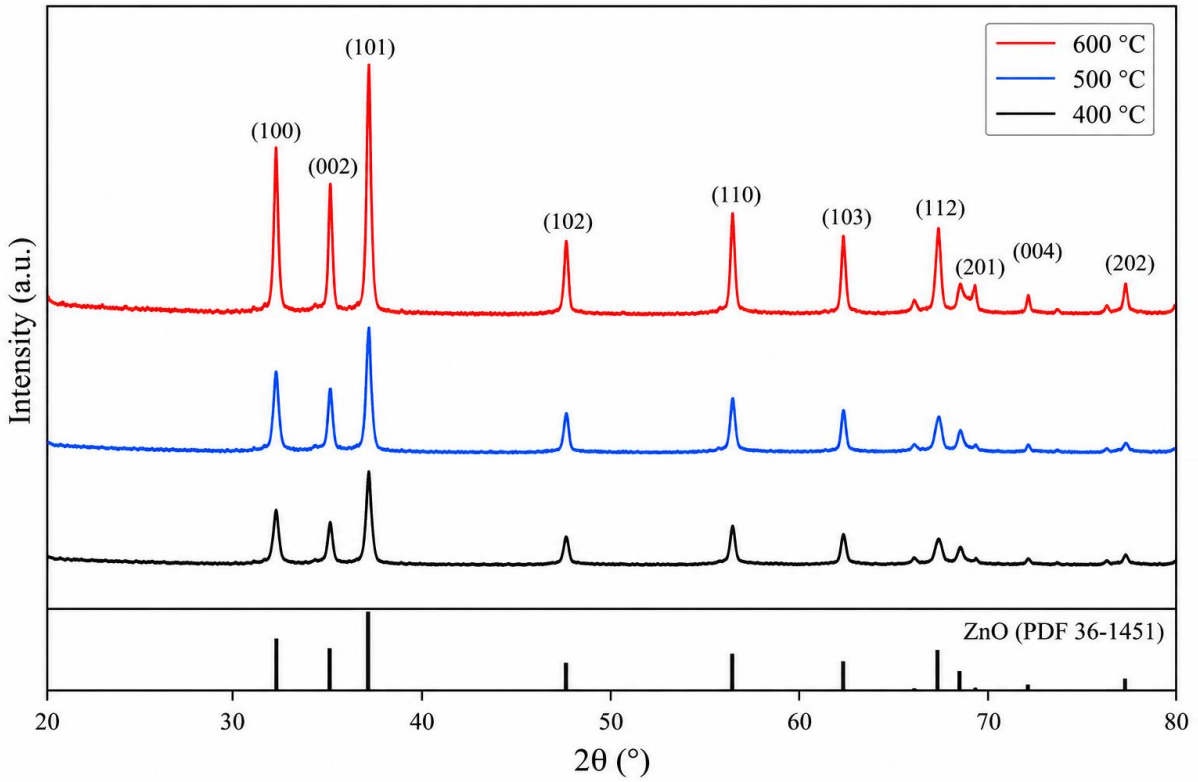


Figure 1. XRD patterns of ZnO nanoparticles synthesized using okra (*Abelmoschus esculentus*) fruit extract and calcined at 400, 500, and 600 °C, with the ZnO reference pattern (PDF 36-1451).

3.2 Morphological analysis (SEM)

The surface morphology of the ZnO nanoparticles calcined at 400, 500, and 600 °C was examined by SEM, and the micrographs are presented in Figure 2. All samples consist of quasi-spherical, slightly faceted nanoparticles that are fused into porous, cauliflower-like aggregates. This aggregated morphology is typical of green-synthesized ZnO and is attributed to the high surface energy of the nanoparticles and to the capping and binding action of the phytochemicals in the okra extract, which link neighboring particles during precipitation and drying. Numerous voids and interparticle pores are visible in all micrographs, which indicates a high accessible surface area.

Annealing temperature has a pronounced effect on particle size and on the degree of aggregation. The sample calcined at 400 °C (Figure 2a) is composed of fine and relatively uniform particles with an average size of approximately 26 nm (range: 15–40 nm). These particles form loosely packed aggregates of about 100–250 nm with an open, highly porous network and well-separated primary particles. When the temperature is raised to 500 °C (Figure 2b), the average particle size increases to approximately 42 nm (25–65 nm), and the particles begin to fuse at their contact points (neck formation), giving rise to denser and larger aggregates of roughly 150–350 nm. At 600 °C (Figure 2c), the particles coarsen considerably to an average size of about 85 nm (50–130 nm). The individual particles are no longer clearly distinguishable, because neighboring grains have merged into large, compact clusters of approximately 250–500 nm with smoother surfaces and a much lower pore density. The particle sizes estimated from the micrographs are summarized in Table 3.

Table 3. Particle and aggregate sizes estimated from the SEM micrographs of ZnO nanoparticles calcined at different temperatures, compared with the crystallite size obtained from XRD (D_{XRD}).

Sample	Primary particle size (nm)	Mean size (nm)	Aggregate size (nm)	D_{XRD} (nm)
400 °C	15–40	26 ± 6	100–250	18.6
500 °C	25–65	42 ± 9	150–350	22.1
600 °C	50–130	85 ± 20	250–500	27.9

This morphological evolution can be explained by thermally activated mass transport. At elevated temperatures, surface and grain-boundary diffusion accelerate, and the system reduces its total surface energy through sintering, neck growth, and coalescence of adjacent nanoparticles (Ostwald-ripening-type coarsening). The removal of the residual organic layer derived from the plant extract at higher temperatures also eliminates the steric barrier between particles and thereby promotes their fusion. The increase in the particle size with temperature is in agreement with the XRD results, where the crystallite size grew from 18.6 nm to 27.9 nm and the microstrain decreased.

It should be noted that the particle sizes determined by SEM are systematically larger than the crystallite sizes calculated with the Debye–Scherrer equation (Table 3). This difference is expected, because the XRD crystallite size represents the size of coherently scattering domains, whereas each particle observed by SEM may consist of several crystallites and includes sintered and aggregated grains. The gap widens at 600 °C (85 nm by SEM versus 27.9 nm by XRD), which suggests that at high temperature the growth is dominated by the coalescence of particles into polycrystalline grains rather than by single-crystal growth alone.

From an application point of view, the 400 °C sample offers small particles, a porous structure, and a large specific surface area, which is advantageous for photocatalytic, sensing, and antibacterial applications, whereas the 600 °C sample, with larger, denser, and better-crystallized grains, is expected to show fewer defects and a more ordered lattice. These morphological differences are expected to affect the optical properties discussed in the next section, since particle size, defect density, and surface states strongly influence light absorption and the band-gap energy.

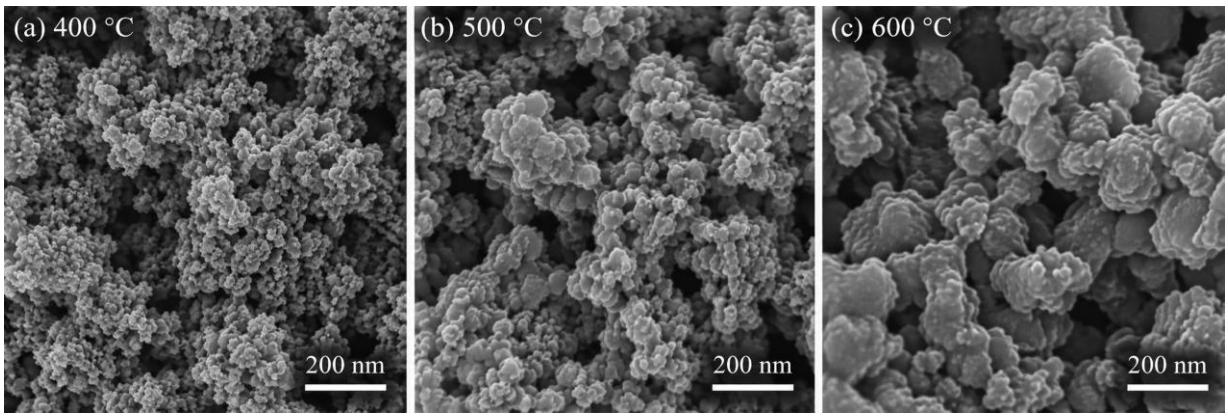


Figure 2. SEM images of ZnO nanoparticles synthesized using okra fruit extract and calcined at (a) 400 °C, (b) 500 °C, and (c) 600 °C (scale bar: 200 nm).

3.3 Optical properties (UV–Vis)

The optical properties of the ZnO nanoparticles calcined at 400, 500, and 600 °C were investigated by UV–Vis absorption spectroscopy in the wavelength range of 200–800 nm, and the results are presented in Figure 3. As shown in Figure 3a, all samples exhibit a strong and well-defined absorption band in the ultraviolet region, with a maximum at approximately 350 nm, followed by a sharp decrease in absorbance toward the visible region. This band originates from the intrinsic band-to-band (O 2p → Zn 3d/4s) electronic transition and the associated excitonic absorption of wurtzite ZnO, and its appearance confirms the formation of ZnO. Beyond the absorption edge (>400 nm), the absorbance remains low and almost flat for all samples, with only a slight rise toward 800 nm that can be attributed to light

scattering from the aggregated nanoparticles. The absence of a distinct absorption band in the visible range indicates that no significant secondary phases or colored impurities are present, which is consistent with the phase-pure wurtzite structure revealed by XRD. The weak features observed in the 220–280 nm range, particularly for the 400 °C sample, may be related to trace amounts of residual organic species from the okra extract, and they become less pronounced as the calcination temperature increases.

Although the position of the main absorption maximum remains nearly unchanged (≈350 nm) with the annealing temperature, the absorption intensity increases systematically in the order 400 °C < 500 °C < 600 °C, and the absorption edge becomes steeper. This enhancement is in line with the improved crystallinity and reduced defect density observed by XRD, since a more ordered lattice with fewer non-radiative and scattering centers gives rise to a sharper and stronger fundamental absorption. The steeper edge of the 600 °C sample also points to a narrower distribution of localized band-tail states.

The optical band gap energy (E_g) of the samples was estimated from the Tauc relation for direct-allowed transitions, which is appropriate for ZnO:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \qquad (6)$$

where α is the absorption coefficient, $h\nu$ is the photon energy, and A is a constant. E_g was obtained by extrapolating the linear portion of the $(\alpha h\nu)^2$ versus $h\nu$ plot to $(\alpha h\nu)^2 = 0$ (Figure 3b). The band gap energies were found to be 3.26, 3.23, and 3.20 eV for the samples calcined at 400, 500, and 600 °C, respectively (Table 4). The corresponding absorption edges, calculated from $\lambda_{edge} = 1240/E_g$, are located at approximately 380, 384, and 388 nm. Thus, increasing the annealing temperature from 400 °C to 600 °C leads to a red shift of the absorption edge and a decrease of the band gap by about 0.06 eV.

Table 4. Optical parameters of ZnO nanoparticles calcined at different temperatures, together with the crystallite size (D_{XRD}), SEM particle size, and microstrain (ε).

Sample	Absorption peak (nm)	Absorption edge (nm)	E_g (eV)	D_{XRD} (nm)	SEM size (nm)	ε ($\times 10^{-3}$)
400 °C	≈352	≈380	3.26	18.6	26	5.85
500 °C	≈352	≈384	3.23	22.1	42	4.94
600 °C	≈352	≈388	3.20	27.9	85	3.90

The band gap values obtained in this study (3.20–3.26 eV) are slightly lower than that of bulk ZnO (≈3.37 eV) but are comparable to the values reported for calcined ZnO nanoparticles in the literature (Sharma et al., 2023). The narrowing relative to the bulk value is generally associated with intrinsic defect states, such as oxygen vacancies and zinc interstitials, which introduce localized levels close to the conduction band and create band tails, as well as with residual phytochemical species on the particle surface.

The decrease of E_g with increasing calcination temperature can be explained by the structural and morphological changes discussed above. As the crystallite size increases from 18.6 nm to 27.9 nm and the particles coalesce into larger grains (Table 4), the contribution of surface and grain-boundary states and of size-related confinement effects diminishes, and the electronic structure approaches that of the bulk crystal. It should be noted, however, that the crystallite sizes are much larger than the exciton Bohr radius of ZnO (≈2.3 nm), so a strong quantum confinement effect is not expected, and the small shift of 0.06 eV is more reasonably related to the changes in crystallinity, lattice strain, and defect-related band tailing. In this respect, the parallel decrease of the microstrain from 5.85×10^{-3} to 3.90×10^{-3} supports the view that the band gap is governed mainly by the relaxation of lattice strain and the growth of the crystallites. Similar red shifts of the band gap upon annealing have been reported for ZnO nanoparticles prepared by green and chemical routes (Karam and Abdulrahman, 2022; Sharma et al., 2023).

Overall, the XRD, SEM, and UV–Vis results are mutually consistent: the increase in the calcination temperature produces larger, better-crystallized, and less strained ZnO particles, which in turn absorb more strongly and possess a slightly narrower band gap. The 400 °C sample, with the widest band gap (3.26 eV), the smallest particles, and the most open porous structure, is expected to be more suitable for surface-dependent applications, whereas the 600 °C sample, with the narrowest band gap (3.20 eV) and the highest crystallinity, is expected to be more favorable for applications that require efficient absorption of near-UV light and low defect density. This confirms that the annealing temperature is a

key parameter for tailoring the structural, morphological, and optical properties of green-synthesized ZnO nanoparticles.

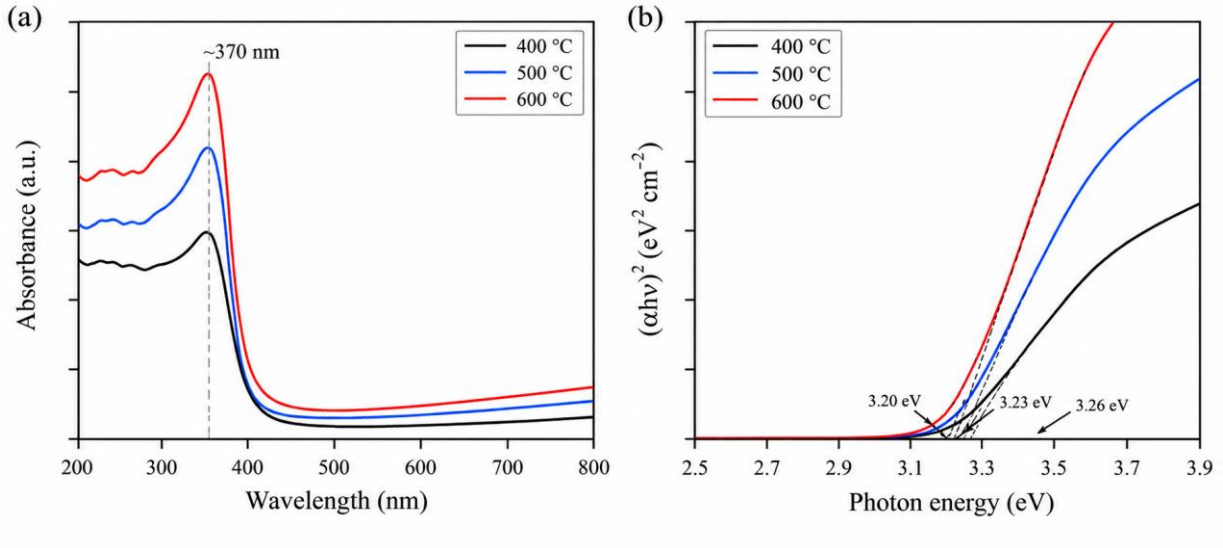


Figure 3. (a) UV–Vis absorption spectra and (b) Tauc plots of ZnO nanoparticles calcined at 400, 500, and 600 °C.

4. CONCLUSIONS

In this study, ZnO nanoparticles were synthesized via a green route using okra (*Abelmoschus esculentus*) fruit extract, and the effect of the calcination temperature (400, 500, and 600 °C) on their structural, morphological, and optical properties was investigated. The main findings are summarized as follows:

(i) XRD analysis confirmed the formation of phase-pure hexagonal wurtzite ZnO (space group $P6_3mc$) at all temperatures, without any secondary phases. Increasing the calcination temperature enhanced the peak intensity and narrowed the reflections; the FWHM of the (101) peak decreased from 0.45° to 0.30°. Accordingly, the average crystallite size increased from 18.6 nm to 27.9 nm, while the dislocation density ($2.88 \rightarrow 1.28 \times 10^{-3}$ nm^{-2}) and the microstrain ($5.85 \rightarrow 3.90 \times 10^{-3}$) decreased, indicating improved crystallinity and relaxation of lattice defects.

(ii) SEM observations showed that the nanoparticles form porous, cauliflower-like aggregates at all temperatures. The average particle size grew from approximately 26 nm at 400 °C to 42 nm at 500 °C and 85 nm at 600 °C, and the particles progressively fused into larger and denser clusters through thermally activated sintering and coalescence.

(iii) UV–Vis measurements revealed a strong absorption band in the UV region at about 350 nm for all samples, whose intensity increased with temperature. The optical band gap, determined from Tauc plots, decreased slightly from 3.26 eV to 3.23 eV and 3.20 eV as the temperature rose from 400 °C to 600 °C. This narrowing was attributed to crystallite growth, lattice strain relaxation, and changes in defect-related band-tail states rather than to quantum confinement.

Overall, the results demonstrate that the calcination temperature is a critical parameter for tuning the crystallinity, particle size, aggregation behavior, and band gap of green-synthesized ZnO nanoparticles. Lower temperatures (400 °C) yield smaller particles with an open porous structure and a wider band gap, which are favorable for surface-dependent applications such as photocatalysis, sensing, and antibacterial use, whereas higher temperatures (600 °C) yield highly crystalline, less strained particles with stronger UV absorption and a narrower band gap. The intermediate temperature (500 °C) offers a compromise between these characteristics. These findings provide a useful basis for selecting the calcination temperature according to the targeted application of okra-mediated ZnO nanoparticles.

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SEPIOLITE AS A SUPPORT MATERIAL IN PHOTOCATALYTIC COMPOSITE SYSTEMS

FOTOKATALİTİK KOMPOZİT SİSTEMLERDE DESTEK MALZEMESİ OLARAK SEPİYOLİT

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Abstract
Sepiolite is a natural clay mineral widely investigated in the design of photocatalytic composites because of its distinctive fibrous structure, high porosity, and large specific surface area. Titanium dioxide (TiO_2), one of the most widely used semiconductor photocatalysts, has limited solar light utilization because its activity is largely restricted to the ultraviolet (UV) region. Numerous studies have therefore explored sepiolite as a matrix and support for semiconductor photocatalysts. Studies on antibiotic removal from aqueous solutions using sol-gel-derived TiO_2/sepiolite composites have shown that sepiolite can outperform zeolite in both adsorption capacity and photocatalytic efficiency. Other systems, including rare-earth (RE)-doped TiO_2/sepiolite and sepiolite/Cu_2O/Cu composites, have also yielded promising results in the photocatalytic degradation of organic dyes. In addition to these composites, pristine sepiolite has been reported to exhibit limited photocatalytic activity under visible light through a dye-sensitized mechanism without further modification. This behavior has been attributed to dye sensitization and the electron-accepting character of broken and terminated Si–O and Mg–O bonds on the sepiolite surface. This review summarizes studies on the use of sepiolite in photocatalytic systems, with an emphasis on composite design, proposed mechanisms, and reported performance.
Keywords: Sepiolite, photocatalysis, TiO_2 composites, dye degradation, support material

Özet
Sepiyolit, kendine özgü fibröz yapısı, yüksek gözenekliliği ve geniş özgül yüzey alanı gibi sahip olduğu üstün fizikokimyasal özellikleri sebebiyle fotokatalitik kompozit malzemelerin tasarımlarında sıklıkla öne çıkan doğal bir kil mineralidir. Günümüzde en yaygın biçimde kullanılan yarı iletken fotokatalizörlerden titanyum diyoksitin (TiO_2) düşük güneş ışığı kullanım verimliliği sergilemesi ve yalnızca ultraviyole (UV) ışık bölgesinde aktifleşebilmesi gibi temel teknik kısıtlamalarını aşmak amacıyla, sepiyolitin yarı iletken fotokatalizörler için son derece uygun bir matris ve destek malzemesi olarak değerlendirildiği çok sayıda farklı bilimsel çalışma literatürde yer almaktadır.
Bu kapsamda, sol-jel yöntemi kullanılarak sentezlenen TiO_2/sepiyolit kompozit yapıları ile sulu çözeltilerdeki antibiyotik türü kirleticilerin giderimi üzerine gerçekleştirilen deneysel çalışmalarda, sepiyolitin sahip olduğu adsorpsiyon kapasitesi ve sağladığı fotokatalitik verimlilik bakımından literatürde yaygın şekilde kullanılan zeolitten belirgin biçimde daha başarılı bir taşıyıcı ve destek malzemesi olduğu tespit edilmiştir. Bunun yanı sıra, nadir toprak elementleri (RE) ile işlevsellendirilip katkılanmış TiO_2/sepiyolit ve sepiyolit/Cu_2O/Cu gibi farklı bileşimlere sahip kompozit sistemler de geliştirilerek çevresel kirletici niteliğindeki organik boyaların fotokatalitik bozunma süreçlerinde uygulanmış ve olumlu sonuçlar elde edilmiştir.
Tüm bu sentezlenmiş kompozit yapılara ek olarak, saf sepiyolitin kendisinin de herhangi bir ilave katkı maddesi bulunmaksızın görünür ışık altında boya ile duyarlılaştırılmış (dye-sensitized) reaksiyon

mekanizmasıyla sınırlı düzeyde fotokatalitik aktivite gösterebildiği belirlenmiştir. Literatürde gerçekleştirilen detaylı çalışmalarda, söz konusu bu özgün davranışın, boya duyarlılaştırmasıyla birlikte sepiyolit yüzeyindeki kırık ve sonlanmış Si–O ve Mg–O bağlarının elektron alıcı karakteriyle ilişkili olduğu önerilmektedir. Bu derleme çalışmasında, sepiyolitin fotokatalitik sistemlerdeki kullanımına, kompozit tasarımlarına ve etki mekanizmalarına dair literatürde yer alan mevcut araştırmalar derlenerek elde edilen sonuçlar sunulmuştur.
Anahtar Kelimeler: Sepiyolit, fotokataliz, TiO_2 kompozitleri, boya bozunumu, destek malzemesi

1. INTRODUCTION

Photocatalysis is an advanced oxidation process in which the absorption of light energy by a semiconductor initiates oxidation and reduction reactions at its surface (Zhao et al., 2025). TiO_2 is among the most extensively studied semiconductors for the photocatalytic degradation of organic pollutants in water and air because of its chemical and photochemical stability, relatively low cost, and strong oxidation capacity (Hoffmann et al., 1995; Carp et al., 2004; Fujishima et al., 2008). However, the band gap of anatase TiO_2, approximately 3.2 eV, largely restricts effective excitation to the UV region (Carp et al., 2004). Furthermore, the recombination of photogenerated electron–hole pairs can limit photocatalytic efficiency by reducing the number of charge carriers available for surface reactions (Hoffmann et al., 1995). Numerous strategies have been developed to address these limitations, including metal or nonmetal doping, coupling with other semiconductors, surface sensitization, and dispersion of the photocatalyst on suitable support materials (Li et al., 2022; Song et al., 2023).

Natural clay minerals have attracted particular interest for the immobilization of semiconductor particles because of their large surface areas, porous structures, adsorption properties, low cost, and surface functional groups. Among these minerals, sepiolite is considered a promising material for carrying and supporting semiconductor phases in photocatalytic composites (Li et al., 2021, 2022).

Sepiolite is a natural magnesium silicate clay mineral with the general formula $[Si_{12}Mg_8O_{30}(OH)_4(H_2O)_4]\cdot 8H_2O$, a fibrous morphology, and a porous channel structure. Its high adsorption capacity, thermal stability, and low cost have led to growing interest in its use as a photocatalyst support. This review examines the use of sepiolite as a support in TiO_2-based composites, its combination with different metal/metal oxide systems, and the limited photocatalytic activity of pristine sepiolite, drawing on findings reported in the literature (Zhang et al., 2011; Zhou et al., 2017).

1.1. Structural properties of sepiolite and its significance as a support material

Sepiolite is a natural clay mineral generally described as a chain-type 2:1 phyllosilicate with a hydrated magnesium silicate composition. Channels extending along discontinuous silicate sheets within its crystal structure, together with its fibrous morphology, give the mineral high porosity and a substantial specific surface area. Silanol groups and coordinatively unsaturated Si–O and Mg–O sites at the surface and edges are important for adsorption and surface interactions. These structural features allow sepiolite to function as more than an inert support: it can also facilitate the dispersion of photocatalyst particles, pollutant adsorption, and the formation of charge-transfer pathways at composite interfaces (Zhou et al., 2017; Chuaicham et al., 2019; Li et al., 2022).

The role of sepiolite in photocatalytic systems can be considered in three respects. First, adsorption helps concentrate pollutant molecules near photocatalytic sites. Second, its fibrous surface promotes a more uniform distribution of nanoparticles, such as TiO2, and limits particle–particle contact. Third, in appropriately designed composites, surface hydroxyl groups and interfacial bonds may indirectly contribute to charge transfer and reactive species formation. The performance of sepiolite-supported systems therefore depends on both the optical properties of the semiconductor and the characteristics of the support–semiconductor interface (Zhang et al., 2011; Li et al., 2021, 2022).

2. TiO_2/SEPIOLTE COMPOSITES: SYNTHESIS, STRUCTURE, AND POLLUTANT REMOVAL

2.1. Low-temperature sol-gel synthesis and organic pollutant removal

Sol-gel synthesis is an important approach to preparing TiO_2/sepiolite composites because it enables a more uniform distribution of the semiconductor phase on the support surface and allows control over particle size (Zhang et al., 2011; Zhou et al., 2017).

Zhang et al. (2011) prepared TiO_2/sepiolite composites by a low-temperature sol-gel method using $TiCl_4$ as the precursor and investigated the influence of the support mineral on the photocatalytic structure. They reported that the ordered crystal structure of sepiolite was partially altered under the synthesis conditions, whereas the size of the TiO_2 particles in the composite could be reduced to below 10 nm. The resulting composites were effective in degrading model pollutants, including Acid Red G (ARG) and 4-nitrophenol (4-NP), under UV irradiation. The authors attributed this performance to the combination of the large surface area provided by sepiolite and the photocatalytically active anatase TiO_2 phase.

These findings illustrate the dual contribution of the sepiolite support. Its large surface area provides adsorption sites for pollutant molecules, while the presence of smaller, dispersed TiO_2 particles on the support may increase the active surface area available for photoexcitation. The broader literature on clay/TiO_2 composites likewise identifies reduced semiconductor aggregation and closer spatial coupling between adsorption and photocatalytic oxidation as key mechanisms underlying improved performance (Zhang et al., 2011; Li et al., 2021).

2.2. Comparison of TiO_2/sepiolite and TiO_2/zeolite: Ofloxacin removal

Sturini et al. compared sol-gel-derived TiO_2/sepiolite and TiO_2/zeolite composites, together with their N-doped counterparts, for the photocatalytic removal of the fluoroquinolone antibiotic ofloxacin. In experiments conducted in tap water, TiO_2/sepiolite and TiO_2/zeolite achieved complete antibiotic removal within 10–15 min, whereas the N-doped counterparts required 20–30 min. A key finding was that sepiolite outperformed zeolite, a commonly used material for pollutant removal, as a TiO_2 support in terms of both adsorption capacity and photocatalytic efficiency. Nitrogen doping reduced the band gap from 3.2 to 3.0 eV, producing a partial shift toward the visible region (Sturini et al., 2020).

These findings also demonstrate that narrowing the band gap alone does not guarantee greater pollutant removal. The actual photocatalytic performance of a composite is governed by the combined effects of several parameters, including pollutant transport to and adsorption on the surface, semiconductor crystal phase and dispersion, the availability of photogenerated charges for surface reactions, and competing species in the water matrix. Selecting an adsorptive support such as sepiolite is therefore a design consideration as important as electronic modification (Sturini et al., 2020; Li et al., 2021).

2.3. Effect of the synthesis method on sepiolite structure and TiO_2 distribution

In sepiolite/TiO_2 composites, both composition and synthesis method determine the preservation of the support structure and the distribution of TiO_2. Zhou et al. (2017) compared conventional calcination with microwave-hydrothermal treatment and showed that calcination at approximately 500 °C and microwave-hydrothermal treatment at approximately 200 °C for 40 min provided suitable conditions for anatase formation. However, high-temperature calcination damaged the ordered structure of sepiolite and reduced its specific surface area. By contrast, microwave-hydrothermal treatment better preserved the fibrous sepiolite structure and produced a more uniform distribution of TiO2 nanoparticles on its surface.

In a subsequent study focusing on Orange G removal, the same research group demonstrated that the performance of microwave-hydrothermally synthesized Sep-TiO_2 composites depended on the Ti/sepiolite ratio and reaction conditions (Zhou et al., 2018). The sample with a Ti/sepiolite ratio of 40 mmol/g exhibited the highest photodegradation activity. Catalyst dosage, initial dye concentration, and pH markedly influenced the reaction kinetics. First-order kinetics were observed under most conditions, whereas the behavior approached zero-order kinetics at high initial dye concentrations. These results support the importance of preserving sepiolite structural integrity and maintaining access to active anatase sites for composite performance.

3. RARE-EARTH-DOPED TiO_2/SEPIOLITE COMPOSITES

One approach to enhancing the visible-light activity of TiO_2 is to modify its electronic structure through doping. Zhou et al. (2019) prepared RE-TiO_2/Sep composites doped with La, Ce, Pr, Nd, Eu, and Gd ions using a microwave-hydrothermal method. RE doping was reported to promote Ti–O–RE bond formation, while RE^{3+} ions located at TiO_2 grain boundaries restricted TiO_2 crystallite growth. XPS results indicated electron transfer from RE to Ti, supporting the formation of Ti–O–RE bonds. The vacant 4f energy levels of RE ions were also described as trapping sites for photogenerated electrons,

whereas surface-adsorbed OH^- groups acted as hole traps. Together, these effects were proposed to facilitate electron–hole separation, reduce recombination, and improve photocatalytic performance under visible light.

However, phase behavior differed among the RE-doped samples. In particular, a small amount of rutile formed in the Gd-TiO_2/Sep sample, and this phase transformation was associated with a decrease in the band gap (Zhou et al., 2019).

The potential contribution of rare-earth doping extends beyond changes in light absorption. Dopant ions may also influence the trapping and recombination of photogenerated charges by altering the distribution of crystal defects and surface energy levels (Zhou et al., 2019).

4. SEPIOLITE/Cu_2O/Cu COMPOSITE SYSTEM AND SUPPRESSION OF PHOTOCORROSION

Cu_2O is a narrow-band-gap semiconductor with a strong visible-light response, but its susceptibility to photocorrosion can limit stability during prolonged use. Wang et al. (2019) developed a ternary sepiolite/Cu_2O/Cu (SCC) composite by immobilizing Cu_2O/Cu nanoparticles on the sepiolite surface. Under simulated solar irradiation, the SCC composite achieved approximately 95.1% Congo Red degradation, compared with approximately 54.3% and 71.2% for Cu2O and Cu2O/Cu, respectively, under the same conditions.

According to the proposed mechanism, metallic Cu accepts photogenerated electrons from Cu2O, limiting their accumulation within Cu_2O and thereby reducing its tendency toward photo-oxidative degradation. Sepiolite provides a scaffold with a large surface area for the semiconductor and metal components, supporting the dispersion of the active phases. The ternary system thus combines visible-light absorption, charge transfer, and structural stability within a single composite (Wang et al., 2019).

5. DYE-SENSITIZED PHOTOCATALYTIC ACTIVITY OF PRISTINE SEPIOLITE

A notable feature of sepiolite is its ability to exhibit limited visible-light activity under certain conditions even without an added semiconductor. Chuaicham et al. (2019) investigated the behavior of unmodified natural sepiolite toward cationic and anionic organic dyes. Cationic dyes showed stronger adsorption on the sepiolite surface and more pronounced photocatalytic degradation. Rhodamine B removal reached 45.3% within 120 min, while methylene blue also exhibited stronger interactions than the anionic dyes. This behavior was explained by a dye-sensitized mechanism rather than conventional semiconductor band-to-band excitation. After absorbing visible light, a dye molecule reaches an excited state and can undergo electron transfer. Coordinatively unsaturated Si–O and Mg–O sites on the sepiolite surface may act as electron acceptors and contribute to charge separation. Subsequent reduction of molecular oxygen can generate superoxide radicals that participate in organic dye degradation. Radical-scavenging experiments identified superoxide radicals as one of the principal reactive species involved in Rhodamine B degradation, supporting this mechanism (Chuaicham et al., 2019).

Pristine sepiolite should therefore not be regarded as a highly active semiconductor photocatalyst. Its observed activity is limited and depends on the light-absorption properties of the dye. Nevertheless, this finding indicates that the sepiolite surface is more than a passive adsorption medium and can participate in photochemical processes through surface defects and coordinatively unsaturated sites (Chuaicham et al., 2019; Li et al., 2022).

6. EMERGING APPLICATIONS OF SEPIOLITE-SUPPORTED PHOTOCATALYSTS

Research on sepiolite-supported photocatalysts is not limited to TiO_2. Recent studies have also investigated the immobilization of other visible-light-active semiconductors on sepiolite. For example, Bai et al. (2022) supported layered WS_2 nanosheets on sepiolite to obtain a synergistic composite for Rhodamine B degradation. This approach was motivated by the tendency of unsupported two-dimensional WS_2 sheets to aggregate, potentially blocking active surfaces. The fibrous structure of sepiolite can serve as a scaffold for dispersing such active phases.

Similarly, Song et al. (2023) decorated natural sepiolite with TiO_2 nanoparticles to develop a composite for indoor formaldehyde removal under sunlight. Synthesis parameters were shown to substantially influence the performance of the TiO_2/sepiolite composite. Such studies demonstrate that sepiolite-supported photocatalysis is expanding beyond aqueous dye solutions to gas-phase pollutants and other

semiconductor classes. Nevertheless, this review primarily focuses on the systems identified in the abstract: TiO_2/sepiolite, rare-earth-doped TiO_2/sepiolite, sepiolite/Cu_2O/Cu, and pristine sepiolite.

7. OVERALL ASSESSMENT OF THE ROLE OF SEPIOLITE IN PHOTOCATALYTIC COMPOSITES

Taken together, the literature findings indicate that the contribution of sepiolite to photocatalytic systems cannot be explained by a single mechanism. First, its high porosity and large surface area promote pollutant adsorption on the composite surface. Because photocatalytic oxidation occurs at the surface, this may shorten the diffusion distance to active semiconductor sites. Second, the fibrous mineral surface provides a scaffold for semiconductor nanoparticle dispersion and helps limit aggregation. Third, surface bonds and defect sites at the support–semiconductor interface may modify the charge-transfer properties of the composite. Fourth, as illustrated by the Cu_2O/Cu system, sepiolite allows multiple components with different functions to be integrated into a single heterogeneous structure (Wang et al., 2019; Li et al., 2021, 2022).

Describing the contribution of sepiolite solely in terms of "high adsorption capacity" is therefore insufficient. An effective photocatalytic composite requires a balance among adsorption, light absorption, charge separation, reactive oxygen species formation, and mass transfer. Excessively strong adsorption may, in some cases, hinder the desorption of reaction products, whereas insufficient semiconductor loading may prevent adsorbed pollutants from contacting enough active sites. Optimizing the semiconductor/sepiolite ratio and selecting an appropriate synthesis method are therefore central to composite design (Zhou et al., 2017, 2018; Li et al., 2021).

7.1. Comparison of representative sepiolite-based photocatalytic systems reported in the literature

System	Synthesis/Modification	Target pollutant	Main finding	Reference
TiO_2/sepiolite	Low-temperature sol-gel	ARG, 4-NP	TiO_2 <10 nm; synergy between a large surface area and anatase	Zhang et al., 2011
TiO_2/sepiolite	Sol-gel	Ofloxacin	Sepiolite showed higher adsorption capacity and photocatalytic performance than zeolite	Sturini et al., 2020
RE-TiO_2/sepiolite	Microwave-hydrothermal; La, Ce, Pr, Nd, Eu, Gd doping	Orange G (OG)	Ti–O–RE formation; restricted TiO_2 crystallite growth and influenced nanoparticle distribution on sepiolite	Zhou et al., 2019
Sepiolite/Cu_2O/Cu	Multicomponent composite	Congo Red (CR)	Metallic Cu suppressed Cu_2O photocorrosion and improved stability	Wang et al., 2019
Pristine sepiolite	Unmodified	RhB, MB, Orange II, Trypan Blue	45.3% RhB removal in 120 min; dye-sensitized mechanism	Chuaicham et al., 2019
Sep-TiO_2	Microwave-hydrothermal/calcination	Orange G	Microwave-hydrothermal treatment better preserved the sepiolite structure and TiO_2 distribution	Zhou et al., 2017, 2018
WS_2/sepiolite	Sepiolite-supported WS_2 nanosheets	RhB	Designed to limit aggregation and promote support–semiconductor synergy	Bai et al., 2022
TiO_2/sepiolite	TiO_2 nanoparticle decoration	Gas-phase formaldehyde	Enhanced photodegradation under sunlight, depending on synthesis parameters	Song et al., 2023

8. CONCLUSINS

The studies reviewed here demonstrate that sepiolite is a versatile support material for photocatalytic composites. Sol-gel-derived TiO_2/sepiolite composites have proved effective in removing organic pollutants and antibiotics, while direct comparative studies have shown that sepiolite can offer higher adsorption capacity and photocatalytic performance than zeolite. More controlled synthesis approaches, such as microwave-hydrothermal treatment, can help preserve the fibrous structure of sepiolite and promote a more uniform distribution of TiO_2 nanoparticles. Rare-earth doping and the incorporation of metal/metal oxide components such as Cu_2O/Cu can improve these systems through distinct mechanisms, including the regulation of crystal growth and charge-carrier behavior and the suppression of photocorrosion, respectively.

The limited dye-sensitized photocatalytic activity of pristine sepiolite under visible light is an important finding that demonstrates that the mineral is not merely a passive support. Nevertheless, its principal strength lies in combining high adsorption capacity, a fibrous and porous morphology, natural availability, and the ability to support different active phases. These properties make sepiolite a low-cost, functional support capable of improving semiconductor dispersion, pollutant accessibility, and composite stability, particularly in TiO_2-based systems. Further investigation of source-mineral standardization, performance in real wastewater matrices, the extent of mineralization, and long-term reusability will enable a more reliable assessment of the practical potential of sepiolite-based systems.

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YEM BİTKİLERİNDE BİTKİ DOKU KÜLTÜRÜ: ÇOĞALTIM, ISLAH VE MODERN BİYOTEKNOLOJİDEKİ UYGULAMALAR

PLANT TISSUE CULTURE IN FORAGE CROPS: APPLICATIONS IN PROPAGATION, BREEDING AND MODERN BIOTECHNOLOGY

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ÖZET
Yem bitkileri; sürdürülebilir hayvansal üretim, kaliteli kaba yem temini ve agroekosistemlerin sürdürülebilirliği bakımından önemli bir bitki grubunu oluşturmaktadır. Artan kuraklık, tuzluluk, sıcaklık stresi ve yem kalitesine yönelik gereksinimler, yüksek verimli ve strese dayanıklı yem bitkilerinin geliştirilmesini zorunlu kılmaktadır. Bu süreçte bitki doku kültürü teknikleri, geleneksel çoğaltım ve ıslah yöntemlerini tamamlayan önemli biyoteknolojik araçlar sunmaktadır. Bu mini derleme; doku kültürünün yem bitkilerindeki mikroçoğaltım, hastalıktan ari bitki üretimi, genetik kaynakların korunması, somatik embriyogenez, in vitro seleksiyon, somaklonal varyasyon ve haploid bitki üretimi gibi başlıca uygulamalarını ele almaktadır. Ayrıca, doku kültürü tekniklerinin kuraklık ve tuzluluk gibi abiyotik streslere toleransın artırılmasındaki potansiyeli ile genetik transformasyon ve CRISPR/Cas temelli genom düzenleme çalışmalarındaki kritik rolü değerlendirilmektedir. Bunun yanı sıra, genotipe bağlı rejenerasyon kapasitesi, somaklonal varyasyon, kontaminasyon, aklimatizasyon ve yüksek üretim maliyetleri gibi temel kısıtlamalar tartışılmaktadır. Sonuç olarak doku kültürü, yem bitkilerinde yalnızca hızlı çoğaltıma yönelik bir yöntem olarak değil; aynı zamanda genetik kaynakların korunması, yeni varyasyonların oluşturulması ve modern biyoteknolojik ıslah uygulamalarının hayata geçirilmesi için stratejik bir platform olarak değerlendirilebilir.
Anahtar Kelimeler: Yem bitkileri; doku kültürü; mikroçoğaltım; in vitro seleksiyon; genetik kaynaklar; bitki ıslahı

ABSTRACT
Forage crops constitute an important group of plants in terms of sustainable animal production, the supply of quality roughage, and the sustainability of agroecosystems. Increasing drought, salinity, heat stress, and requirements for forage quality necessitate the development of high-yielding and stress-tolerant forage crops. In this process, plant tissue culture techniques offer important biotechnological tools that complement traditional propagation and breeding methods. This mini-review addresses the main applications of tissue culture in forage crops, such as micropropagation, disease-free plant production, conservation of genetic resources, somatic embryogenesis, in vitro selection, somaclonal variation, and haploid plant production. Furthermore, the potential of tissue culture techniques in improving tolerance to abiotic stresses such as drought and salinity, and their critical role in genetic transformation and CRISPR/Cas-based genome editing studies are evaluated. In addition, key limitations such as genotype-dependent regeneration capacity, somaclonal variation, contamination, acclimatization, and high production costs are discussed. In conclusion, tissue culture can be considered not only a method for rapid multiplication in forage plants, but also a strategic platform for the conservation of genetic resources, the creation of new variations, and the activation of modern biotechnological breeding practices.

Keywords: Forage crops; tissue culture; micropropagation; in vitro selection; genetic resources; plant breeding

INTRODUCTION

Forage crops constitute one of the fundamental components of animal production systems, directly determining forage yield and quality while making a significant contribution to the sustainability of agroecosystems. This plant group, which encompasses a broad spectrum of species ranging from grassland and rangeland plants to legume and grass forages, meets the basic raw material requirements of the global livestock sector (El-Sherif, 2018). However, the conventional breeding and propagation of these plants involves numerous challenges. Classical cross-breeding-based improvement processes are time-consuming and are further constrained by genetic barriers such as seasonal limitations, insufficient intraspecific genetic variation, and interspecific cross-incompatibilities, all of which hinder the widespread adoption of high-quality genotypes. Moreover, genetic losses arising from viruses and other pathogens continue to pose a serious threat to the production continuity of forage crops (Gogile et al., 2025).

Abiotic stress conditions such as drought, high salinity, and extreme temperature—increasingly pronounced with global climate change—adversely affect existing cultivation areas and reduce the productivity of forage crops. This situation highlights the urgent need for the rapid development of high-yielding, stress-tolerant new genotypes. While conventional breeding methods are insufficient on their own to meet these demands, modern biotechnological approaches are introducing a new dimension to the process (Encina & Regalado, 2022).

Plant tissue culture is a biotechnological platform that enables the propagation of plant material at the cellular and tissue level under sterile conditions and its subsequent regeneration into whole plants. This platform offers multifaceted advantages, including rapid and season-independent propagation, production of disease-free material, in vitro conservation of genetic resources, and integration with modern genetic engineering applications. Incorporating techniques such as micropropagation, organogenesis, somatic embryogenesis, meristem culture, in vitro selection, and haploidization, tissue culture has gained recognition as a comprehensive set of tools that goes beyond the limits of classical methods in forage crop improvement (Shahzad et al., 2017).

This mini-review systematically addresses the principal applications of tissue culture techniques in forage crops, their contribution to breeding programs, their role in enhancing abiotic stress tolerance, and their interaction with genetic transformation and CRISPR/Cas-based genome editing studies. In addition, current limitations hindering the wider adoption of the technology and future development perspectives are discussed.

TISSUE CULTURE TECHNIQUES AND APPLICATIONS IN FORAGE CROPS

Plant tissue culture is a broad biotechnological field encompassing numerous techniques. These techniques serve critical functions in forage crops, including rapid propagation, production of disease-free material, genetic improvement, and long-term conservation of genetic resources (Loyola-Vargas & Ochoa-Alejo, 2018).

Micropropagation and Organogenesis

Micropropagation is a tissue culture application that enables the rapid clonal propagation of selected superior genotypes under sterile conditions throughout the year, independent of seasonal constraints. Through this technique, genetically faithful (*true-to-type*) and disease-free plant material is obtained, thereby ensuring continuity in production and minimizing the risk of genetic variation inherent in seed-based propagation (Algopishi et al., 2025; Shahzad et al., 2017).

Organogenesis is the process by which organs such as roots and shoots are regenerated from sterile explants under *in vitro* conditions. This process can occur directly—through development from the meristem of an existing organ—or indirectly, first through callus formation followed by organ differentiation. The type, concentration, and combination of plant growth regulators, along with explant type and genotype, are among the primary factors determining organogenesis efficiency (Shahzad et al., 2017). Optimization of organogenesis protocols in legume forage crops, in particular, opens the way for rapid propagation at a commercial scale.

Somatic Embryogenesis

Somatic embryogenesis is a technique by which embryo-like structures (somatic embryos) are generated from somatic cells or tissues, enabling the development of new plants without sexual reproduction. This method, which is preferred particularly for large-scale clonal propagation, offers higher multiplication rates compared to organogenesis and provides a basis for advanced applications such as synthetic seed production (Brown & Thorpe, 1995). Somatic embryos can be encapsulated in artificial coatings to produce synthetic seeds, facilitating long-distance transport and extended storage (Shahzad et al., 2017). The efficient application of somatic embryogenesis in forage crops depends on the optimization of plant growth regulators and the determination of genotype-specific culture conditions.

Meristem Culture and Disease-Free Plant Production

Meristem culture is based on the culture and propagation of actively dividing cells derived from apical meristems or nodal explants under sterile conditions. Since active meristematic regions are largely free of plant pathogens—particularly viruses—the production of healthy, disease-free plant material from such regions is feasible. This method is widely applied as a standard protocol for virus elimination in commercially important cultivars and propagation material (Algopishi et al., 2025; Delgado-Paredes et al., 2021). The adoption of meristem culture in the production of certified seed or seedling material in forage crops could substantially reduce crop losses attributable to plant diseases.

***In Vitro* Conservation of Genetic Resources and Cryopreservation**

Genetic erosion and habitat degradation are progressively narrowing the gene pool of forage crops. Tissue culture techniques enable the long-term conservation of rare endemic species, local varieties, and commercially important genotypes under *in vitro* conditions (Delgado-Paredes et al., 2021). By suppressing active growth through slow-growth cultures and medium modifications, plant material can be kept viable over the medium term.

Cryopreservation involves the long-term preservation of plant material at the tissue, cell, or organ level by freezing in liquid nitrogen at −196°C. This method allows the viability and genetic integrity of the genetic material to be maintained for decades, minimizing risks of biological degradation and genetic loss. Cryopreservation stands out as a critical tool for establishing an indispensable genetic resource pool for breeding programs (Delgado-Paredes et al., 2021; Gosal et al., 2010).

Somaclonal Variation

During the course of tissue culture, spontaneous genetic changes—known as somaclonal variations—may arise in plants in association with extended periods in culture. These variations encompass a broad spectrum ranging from DNA mutations to epigenetic modifications and epiallelic variations. In commercial micropropagation, somaclonal variation is considered undesirable as it leads to clonal inconsistency. Nevertheless, in forage crop species with a narrow genetic base, these variations can be deliberately exploited to generate new sources of genetic diversity (Brown & Thorpe, 1995; Krishna et al., 2016). To ensure clonal reliability in commercial propagation, the application of molecular marker-based genetic fidelity testing is of paramount importance.

ROLE OF TISSUE CULTURE IN FORAGE CROP BREEDING AND THE ENHANCEMENT OF STRESS TOLERANCE

Plant tissue culture techniques make tangible contributions to forage crop breeding through approaches such as *in vitro* selection, somaclonal variation, haploidization, and embryo rescue. These approaches play a decisive role particularly in the identification and development of genotypes resistant to abiotic stress factors such as drought, high salinity, and extreme temperature.

***In Vitro* Selection**

In vitro selection is a screening method based on directly exposing plants to specific abiotic stresses, such as drought and salinity, under controlled laboratory conditions. This approach can be carried out more rapidly and at lower cost compared to classical field-based selection, enabling the identification of tolerant cells or tissues and the subsequent regeneration of plants retaining stress resistance from those tissues (Wijerathna-Yapa & Hiti-Bandaralage, 2023). The adoption of this method in forage crop breeding programs shortens selection cycles and provides a reproducible and standardized screening environment that is independent of field size.

Exploiting Somaclonal Variation in Breeding

Somaclonal variations arising through spontaneous mutations and epigenetic modifications during tissue culture generate new sources of genetic diversity. When directed in a controlled manner, these variations can serve as a functional tool for obtaining new genotypes with enhanced tolerance to drought, salinity, and temperature stresses in forage crop species characterized by a narrow genetic base (Brown & Thorpe, 1995; Krishna et al., 2016). However, confirmation of the phenotypic and genetic stability of obtained variants is recognized as a mandatory prerequisite before inclusion in breeding programs.

Haploidization Techniques

The production of haploid and doubled haploid plants through anther or microspore culture significantly accelerates breeding processes. Doubled haploid lines make it possible to obtain fully homozygous individuals in a single generation without segregating hybridization. This method enables the stable transfer of stress tolerance traits identified through *in vitro* selection into fixed and homozygous genotypes, thereby substantially reducing variety development timelines compared to classical breeding methods (Anis & Ahmad, 2016; Brown & Thorpe, 1995). The wider use of haploidization in forage crops directly contributes to the rapid development of fixed varieties and the enhancement of breeding program efficiency.

Embryo Rescue

Embryo rescue refers to the in vitro culture and maturation of hybrid embryos that abort due to genetic incompatibility or experience developmental arrest caused by stress, followed by their regeneration into whole plants. Cross-incompatibility barriers encountered in interspecific hybridization restrict the transfer of stress tolerance genes from wild relatives into cultivated varieties. Embryo rescue overcomes these barriers, paving the way for access to a broader gene pool for drought, salinity, and temperature tolerance in forage crops (Algopishi et al., 2025; Brown & Thorpe, 1995).

***In Vitro* Investigation of Stress Tolerance Mechanisms**

Tissue culture environments provide controlled and reproducible experimental platforms amenable to the in-depth investigation of physiological and biochemical mechanisms associated with stress tolerance. Through these platforms, mechanisms such as proline accumulation in response to osmotic stress, scavenging of reactive oxygen species, and stress-specific gene expression changes can be examined in detail. Proline accumulation has been shown to exhibit a strong correlation with salinity and drought tolerance, and this finding is recognized as a biochemical marker that can be utilized in *in vitro* selection programs (Alhasnawi, 2019).

The integration of molecular biology and omics technologies with tissue culture is accelerating the characterization of stress-responsive genes and their incorporation into breeding programs. Transgenic approaches have markedly enhanced stress tolerance in various crop plants by transferring genes controlling osmolyte biosynthesis, detoxification of reactive oxygen species, and stress-responsive transcription factors. Tissue culture serves a central function in executing these genetic interventions and in validating the resulting modified plants under *in vitro* conditions before their deployment in field settings (Brown & Thorpe, 1995; Farooqi et al., 2022; Wani et al., 2016).

ROLE OF TISSUE CULTURE IN GENETIC TRANSFORMATION AND GENOME EDITING

Recent advances in genetic transformation and genome editing technologies have fundamentally transformed the improvement of key agronomic traits in forage crops, including forage yield, quality, digestibility, and stress tolerance. In the implementation of these technologies, tissue culture serves as an indispensable platform for plant regeneration and verification of genetic modification.

Agrobacterium-Mediated Genetic Transformation

Agrobacterium tumefaciens-mediated genetic transformation remains one of the most widely used and effective methods for the introduction of foreign genes into plant genomes. The biological capacity of this bacterium to naturally transfer T-DNA into plant cells enables stable transgene integration and can be performed at relatively low cost. *Agrobacterium*-mediated transformation has been successfully applied to confer traits enhancing biomass yield, nutritional content, digestibility, and resistance to abiotic stress factors such as drought, salinity, and extreme temperature in various plant species (Rahman et al., 2023; Yang et al., 2024).

Nevertheless, the method has certain limitations. Recalcitrance to *Agrobacterium* observed in many plant species, low transformation efficiency in certain crops, and the risk of off-target integration are among the foremost constraints. The continuous optimization of genotype-specific protocols is adopted as the primary strategy for overcoming these issues.

CRISPR/Cas-Based Genome Editing

The CRISPR/Cas system is regarded as a revolutionary technology enabling precise and highly efficient genome editing in plants. This system encompasses various levels of intervention—including targeted gene knockdown, gene insertion, transcriptional modulation, epigenetic modifications, and base editing—significantly expanding the range of possible interventions in forage crop genomes (Che et al., 2022; Prado et al., 2024).

The application of the CRISPR/Cas system to plants is accomplished via *Agrobacterium*-mediated transformation, particle bombardment, or protoplast transfection, all of which require efficient tissue culture systems. This technology has been effectively applied to traits directly related to forage quality and yield, such as improving cell wall digestibility, enhancing nutritional profiles, and developing stress tolerance (Che et al., 2022; Prado et al., 2024).

The Central Role of Tissue Culture in Transformation and Regeneration

Successful genetic transformation depends on efficient tissue culture systems that enable productive plant regeneration from modified cells. A significant advance in this area is the ability of the *WUSCHEL2 (WUS2)* gene to trigger direct somatic embryo formation in genotypes with high regeneration capacity, thereby bypassing the callus phase and shortening the transformation cycle. This innovation has markedly improved transformation efficiency and regeneration rates across diverse plant genotypes (Altpeter et al., 2016; Che et al., 2022).

The genotype-dependency and lengthy processes associated with tissue culture have prompted researchers to develop tissue culture-independent alternative transformation methods. In this context, *in planta* transformation—whereby genome editing is achieved through *Agrobacterium* infiltration of cut coleoptiles—has emerged as a promising approach. However, the applicability of this method across species remains limited at present (Quiroz et al., 2024; Tamizi et al., 2023).

Integration of Nanotechnology with Tissue Culture

Nanomaterials are attracting increasing research interest as innovative gene delivery systems capable of overcoming the limitations of conventional gene transfer methods—such as tissue damage, low efficiency, and species dependence. With their capacity to protect nucleic acids under adverse conditions and deliver them more effectively to target cells, nanoparticles hold potential for improving transformation and regeneration rates in forage crops. Although this field is still in its early stages, it is expected to assume an important complementary role alongside tissue culture and genetic engineering techniques in the future (Yan et al., 2022; Pathak et al., 2023).

Applications in Improving Forage Yield, Quality, Digestibility, and Stress Tolerance

Genetic transformation and genome editing technologies are used in a complementary fashion to improve key agronomic traits in forage crops:

With regard to forage yield and quality, genes controlling biomass production and nutritional composition are targeted to increase forage volume and improve crude protein content. Large-scale propagation of genetically superior genotypes is accomplished through tissue culture.

With regard to digestibility, targeting genes involved in cell wall biosynthesis through CRISPR/Cas increases the digestibility of cellulose and lignin, directly improving animal nutrition and feed efficiency.

With regard to abiotic stress tolerance, CRISPR-based edits and transgenic approaches strengthen drought, salinity, and temperature tolerance in key forage crop species by modulating stress-responsive genes (Surya Krishna et al., 2023; Wani et al., 2016).

With regard to disease resistance, *Agrobacterium* and CRISPR technologies enable the introduction of genes conferring pathogen resistance or the optimization of existing defense mechanisms in the plant.

LIMITATIONS, FUTURE PERSPECTIVES, AND CONCLUSIONS

Despite harboring tremendous potential in the breeding and sustainable production of forage crops, plant tissue culture still faces significant constraints that impede its widespread application.

Genotype Dependency and Low Regeneration Capacity
Tissue culture regeneration efficiency varies markedly across plant species and genotypes. In many economically important species such as alfalfa and rye, organogenesis and somatic embryo formation are highly dependent on genotype-specific culture conditions, which slows the progress of breeding and genetic transformation efforts (Hossein Pour et al., 2019; Ray & Bingham, 1989). The type and concentration of growth regulators, explant source, and culture medium composition are among the critical parameters that directly influence regeneration success.

Concerns Related to Somaclonal Variation
Somaclonal variations arising during extended culture periods and at high subculture numbers are considered undesirable from a commercial micropropagation perspective, as they disrupt clonal homogeneity and threaten quality assurance. On the other hand, controlled somaclonal variation in forage crop species with a narrow genetic base offers a potential advantage for generating new sources of genetic diversity. Molecular marker-based genetic stability testing has become a mandatory standard for managing this balance (Heinze & Schmidt, 1995; Karp, 1995).

Acclimatization Challenges
In vitro-grown plants are physiologically adapted to high humidity, low light intensity, and sterile culture conditions. During their transition to a climate-controlled outdoor environment—the acclimatization phase—water stress and pathogen pressure can result in high mortality rates. Protocol optimizations such as stepwise hardening chambers and specialized humidity control systems substantially reduce losses at this stage (Nelson et al., 2025).

Cost and Labor Intensity
Requirements for sterile infrastructure, nutrient media, energy consumption, and specialized personnel make tissue culture applications highly costly. In developing countries in particular, this economic burden constitutes one of the primary obstacles to the wider adoption of the technology in agricultural applications. Advances in automation, robotic systems, and high-throughput screening protocols hold tangible potential for reducing production costs and improving process efficiency (Alam, 2025; Quiroz et al., 2024).

Future Perspectives
Looking ahead, several key approaches are emerging that will expand the effectiveness and scope of application of tissue culture technology.
Use of morphogenetic regulatory genes: The application of morphogenesis-promoting transcription factors such as *WUS2* and *BABY BOOM* increases regeneration capacity even in recalcitrant genotypes, substantially alleviating the problem of genotype dependency (Maharjan et al., 2025; Nelson et al., 2025).
Tissue culture-independent transformation methods: Innovative approaches such as *in planta* transformation and nanoparticle-based gene delivery systems offer potential for eliminating the steps requiring conventional tissue culture, thereby shortening turnaround times and reaching a broader range of genotypes (Quiroz et al., 2024).
Transgene-free genome editing strategies: Transgene-free editing strategies based on the use of ribonucleoprotein (RNP) complexes or viral vectors present a critical opportunity both for reducing regulatory barriers and for increasing consumer acceptance (Gong et al., 2021; Surya Krishna et al., 2023).
Artificial intelligence and omics integration: Integration of artificial intelligence and machine learning platforms into tissue culture processes accelerates the optimization of regeneration conditions; targeted breeding approaches supported by genomic, transcriptomic, and metabolomic data make it possible to identify genes controlling stress tolerance and forage quality with far greater speed and accuracy (Farooqi et al., 2022).

CONCLUSIONS
Plant tissue culture is a strategic biotechnological platform encompassing a broad range of functions, from micropropagation and disease-free plant production to genetic transformation and CRISPR/Cas-mediated genome editing. This platform has established itself as a powerful complement to conventional breeding methods for overcoming the primary constraints limiting yield, quality, and resilience in forage

crops. Current limitations such as genotype dependency, high cost, and acclimatization continue to be addressed, with advances in automation, nanotechnology, and artificial intelligence accelerating this process. In light of all these developments, tissue culture will assume growing importance in the coming years in consolidating the critical role of forage crops within sustainable agricultural and livestock systems.

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FARKLI SORGUM (SORGHUM BICOLOR L.) VE YONCA (MEDICAGO SATIVA L.) KARIŞIM ORANLARININ SİLAJ FERMANTASYONU VE BESİN ÖZELLİKLERİ ÜZERINE ETKİLERİ

EFFECTS OF DIFFERENT SORGHUM (SORGHUM BICOLOR L.) AND ALFALFA (MEDICAGO SATIVA L.) MIXTURE RATIOS ON SILAGE FERMENTATION AND NUTRIENT PROPERTIES

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ÖZET
Bu araştırma, sorgum ve yoncanın farklı oranlarda karıştırılmasıyla hazırlanan silajların fermantasyon ve yem kalitesi özelliklerinin ortaya konulması amacıyla yürütülmüştür. Deneme, beş karışım oranı (%100 Sorgum; %70 Sorgum + %30 Yonca; %50 Sorgum + %50 Yonca; %30 Sorgum + %70 Yonca; %100 Yonca) ve üç tekerrürlü olarak kurulmuştur. Silaj örneklerinde pH, kuru madde, ham protein, ham selüloz, ham kül, NDF, ADF ve ADL değerleri belirlenmiş; veriler varyans analizi (ANOVA) ve Duncan çoklu karşılaştırma testi kullanılarak değerlendirilmiştir. Kuru madde ($p<0,05$) dışında, karışım oranları arasındaki farklar tüm özellikler bakımından önemli ($p<0,01$) bulunmuştur. Silaj pH'sı yonca oranı arttıkça yükselmiş; en düşük pH %100 sorgum (3,73), en yüksek pH %100 yonca (5,19) silajında ölçülmüştür. Bu sonuç, baklagil yem bitkisi olan yoncanın yüksek tampon kapasitesi nedeniyle fermantasyonu nispeten güçleştirdiğini göstermektedir. Ham protein içeriği yonca oranıyla belirgin şekilde artmış, %100 sorgumda %7,86'dan %100 yoncada %16,56'ya yükselmiştir. Hücre çeperi bileşenleri (NDF, ADF, ADL) ve ham selüloz içerikleri sorgum oranı arttıkça yükselirken, ham kül içeriği en yüksek %100 yonca (%12,81) silajında belirlenmiştir. Sonuç olarak, sorgumun düşük pH ile öne çıkan üstün fermantasyon özelliği ile yoncanın yüksek protein katkısı birlikte değerlendirildiğinde, her iki bitkinin avantajlarını birleştiren %50 Sorgum + %50 Yonca ve %30 Sorgum + %70 Yonca karışımlarının hem yeterli fermantasyon hem de yüksek besin değeri sağlayan uygun karışım oranları olarak önerilebileceği sonucuna varılmıştır.
Anahtar kelimeler: Silaj, Sorgum (*Sorghum bicolor* L.), Yonca (*Medicago sativa* L.), Karışım oranı, Fermantasyon, Yem kalitesi

ABSTRACT
This research was conducted to reveal the fermentation and feed quality characteristics of silages prepared by mixing sorghum and alfalfa at different ratios. The experiment was established with five mixture ratios (100% Sorghum; 70% Sorghum + 30% Alfalfa; 50% Sorghum + 50% Alfalfa; 30% Sorghum + 70% Alfalfa; 100% Alfalfa) and three replications. pH, dry matter, crude protein, crude fiber, crude ash, NDF, ADF and ADL values were determined in the silage samples; the data were evaluated using analysis of variance (ANOVA) and Duncan's multiple comparison test. Except for dry matter ($p<0.05$), the differences among the mixture ratios were found to be significant ($p<0.01$) for all traits. Silage pH increased as the alfalfa ratio increased; the lowest pH was measured in the 100% sorghum (3.73) and the highest in the 100% alfalfa (5.19) silage. This result indicates that alfalfa, a legume forage, relatively hampers fermentation owing to its high buffering capacity. Crude protein content increased markedly with the alfalfa ratio, rising from 7.86% in 100% sorghum to 16.56% in 100% alfalfa. While cell wall components (NDF, ADF, ADL) and crude fiber contents increased as the sorghum ratio

increased, the crude ash content was highest in the 100% alfalfa (12.81%) silage. In conclusion, when the superior fermentation feature of sorghum, distinguished by its low pH, and the high protein contribution of alfalfa are evaluated together, it was concluded that the 50% Sorghum + 50% Alfalfa and 30% Sorghum + 70% Alfalfa mixtures, which combine the advantages of both crops, can be recommended as suitable mixture ratios providing both adequate fermentation and high nutritive value.
Keywords: Silage, Sorghum (*Sorghum bicolor* L.), Alfalfa (*Medicago sativa* L.), Mixture ratio, Fermentation, Feed quality

INTRODUCTION

Silage production is a widely adopted method of forage conservation that enables the storage of high-moisture plant material through anaerobic lactic acid fermentation. The quality of the resulting silage is determined by the interaction of multiple factors, including plant species, chemical composition at harvest, dry matter content, and the ratio in which different forage crops are combined when mixed prior to ensiling. Selecting appropriate forage combinations represents an effective and low-cost strategy to simultaneously optimize fermentation characteristics and nutritive value (Chen et al., 2018a; Tao et al., 2019).

Sorghum (*Sorghum bicolor* L.) is a high-yielding, drought-tolerant cereal forage crop that has gained considerable importance in silage production, particularly in semi-arid and water-limited regions. Its relatively high content of water-soluble carbohydrates (WSC) provides readily fermentable substrate for lactic acid bacteria (LAB), enabling efficient acidification and a characteristically low final pH. Harvest at the milk stage maximizes fermentation efficiency, with beneficial microbial consortia dominated by Lactobacillus and Leuconostoc becoming established at later maturities, further improving fermentation profile and rumen fermentation efficiency (Zhao et al., 2025). Cultivar selection also plays a role in determining silage quality, as grain-type sorghum cultivars exhibit higher starch and crude protein contents compared to conventional forage types, offering an improved balance of yield and nutritive value (Zhang et al., 2025). Additionally, approaches such as supplementation with oil-extracted microalgae, cottonseed cake combined with microbial inoculants, and inoculation with LAB strains have been shown to further boost protein content and fermentation stability of sorghum silage (Chen et al., 2018b; Khota et al., 2017; Mendes et al., 2025). Despite these advantages, the crude protein (CP) content of sorghum silage typically ranges between 7 and 10% on a dry matter basis, which is insufficient to meet the nutritional requirements of high-producing dairy cows or rapidly growing beef cattle when used as the sole roughage source.

Alfalfa (*Medicago sativa* L.) is the most widely cultivated perennial forage legume, distinguished by its high CP content, favourable amino acid profile, and rich mineral composition. However, ensiling pure alfalfa presents well-documented technical challenges. Its high buffering capacity -- arising from proteins, organic acids, and mineral cations -- requires a substantially greater amount of lactic acid to achieve the pH reduction necessary for adequate preservation. Compounding this, alfalfa is inherently low in WSC, limiting the substrate available for LAB activity and slowing the rate of acidification. The resulting elevated final pH increases the risk of clostridial fermentation, excessive proteolysis, and ammonia nitrogen accumulation, all of which degrade silage quality and palatability (Li et al., 2016; Luo et al., 2021; Tao et al., 2019). Strategies investigated to address these limitations include supplementation with fermentable carbohydrate sources such as molasses, application of LAB inoculants and cellulase enzymes, use of chemical additives such as sodium diacetate, incorporation of biochar, and blending with carbohydrate-rich forages (Esen et al., 2023; Gulumser et al., 2024; Guo et al., 2021; Su et al., 2019).

Co-ensiling sorghum and alfalfa exploits the complementary properties of these two forage species: sorghum supplies the fermentable carbohydrates and dry matter needed to drive rapid lactic acid fermentation and lower pH, while alfalfa contributes protein and minerals that improve the nutritive value of the mixture. Studies evaluating sweet sorghum and alfalfa mixtures at varying proportions have demonstrated that increasing alfalfa content raises CP and aerobic stability but progressively elevates silage pH due to alfalfa's greater buffering capacity, whereas higher sorghum proportions promote lactic acid production, lower pH, and reduce proteolytic nitrogen losses (Chen et al., 2018b; Tao et al., 2019). Similar synergistic benefits have been reported when alfalfa is co-ensiled with other high-WSC crops such as maize, Sudan grass, and peanut vine, confirming that carbohydrate-rich co-substrates consistently improve fermentation efficiency in legume-based silages (Dawuti et al., 2024; Sun et al.,

2023). The mixture ratio between the two species is therefore the critical variable that governs the trade-off between fermentation quality and protein supply, and identifying the optimal ratio requires systematic evaluation across the full compositional spectrum.

Although the general benefits of mixing sorghum with alfalfa have been reported in the literature, detailed and simultaneous information on the fermentation and chemical composition responses -- including cell-wall fractions -- across the complete range of binary mixture ratios from 100% sorghum to 100% alfalfa remains limited under controlled micro-silo conditions. Such data are essential for evidence-based recommendations in mixed silage programs. Accordingly, this study aimed to determine the effects of five sorghum-alfalfa mixture ratios (100% Sorghum; 70% Sorghum + 30% Alfalfa; 50% Sorghum + 50% Alfalfa; 30% Sorghum + 70% Alfalfa; 100% Alfalfa) on silage pH, dry matter, crude protein, crude fiber, crude ash, NDF, ADF, and ADL, and to identify the ratio that most effectively balances fermentation quality with nutritive value for use in ruminant feeding programs.

MATERIALS and METHODS

Sorghum (*Sorghum bicolor* L.) was harvested at the milk stage and alfalfa (*Medicago sativa* L.) at the full flowering stage, both corresponding to the growth windows recommended for optimal silage yield and quality. Harvested material from each species was chopped independently to a uniform particle length of 2-3 cm using a stationary forage chopper. Five mixture ratios were then prepared on a fresh weight basis: 100% Sorghum (S100), 70% Sorghum + 30% Alfalfa (S70A30), 50% Sorghum + 50% Alfalfa (S50A50), 30% Sorghum + 70% Alfalfa (S30A70), and 100% Alfalfa (A100). The chopped materials were weighed and thoroughly mixed by hand to achieve a homogeneous blend at each target ratio. Each mixture was then filled into vacuum-sealed polyethylene micro-silo bags in approximately 2 kg portions, manually compressed to expel residual air, and sealed airtight. The bags were incubated at 24 ± 2 °C in a dark room for 60 days. Three independent bags were prepared per treatment, yielding 15 micro-silos in total.

At the end of the 60-day ensiling period, bags were opened and representative sub-samples were immediately collected for analysis. Silage pH was measured by blending approximately 30 g of fresh silage with 270 mL of deionised water for 60 seconds, allowing the suspension to stand for 30 minutes, and then reading the filtered extract with a temperature-compensated digital pH meter (Mettler Toledo Seven Compact, Switzerland). For dry matter (DM) content, approximately 500 g of fresh silage was oven-dried at 70 °C to constant mass; the dried residue was then finely ground to pass through a 1 mm sieve and stored in sealed containers until further analysis. Crude protein (CP; Kjeldahl N × 6.25) and crude ash (CA; combustion at 550 °C in a muffle furnace) were determined in accordance with AOAC (1990). Crude fiber (CF) was quantified by sequential acid-alkali digestion following standard procedures. Neutral detergent fiber (NDF; with the addition of sodium sulphite and heat-stable alpha-amylase), acid detergent fiber (ADF), and acid detergent lignin (ADL) were determined sequentially using an ANKOM 200 Fiber Analyzer (ANKOM Technology, NY, USA) according to ANKOM Tech Methods (2017). All analytical results are reported on a DM basis unless stated otherwise.

Experimental data were analysed by one-way analysis of variance (ANOVA) using SAS statistical software (SAS, 1999) under a completely randomized design with three replications, with sorghum-alfalfa mixture ratio as the single treatment factor. Where ANOVA detected a statistically significant effect ($p<0.05$ or $p<0.01$), treatment means were separated using Duncan's multiple range test. Differences among treatment means were considered significant at $p<0.05$ or $p<0.01$ as indicated.

RESULTS

Mixture ratio significantly affected all measured traits: all parameters except dry matter were significant at $p<0.01$, while dry matter was significant at the $p<0.05$ level (Table 1). Silage pH rose progressively with increasing alfalfa proportion, from 3.73 in S100 to 5.19 in A100; the three lowest-sorghum treatments (S100, S70A30, S50A50) were statistically indistinguishable in pH, whereas S30A70 and A100 formed distinct higher groups. Dry matter showed a relatively narrow but significant gradient (24.94 to 25.66%), with S100 and S70A30 being the lowest and A100 the highest group. Crude protein increased sharply and monotonically with alfalfa inclusion, from 7.86% (S100) to 16.56% (A100), with every treatment forming a separate statistical group. Crude fiber and the cell-wall fractions (NDF, ADF) decreased with higher alfalfa proportion: NDF fell from 61.19% (S100) to 40.98% (A100), and ADF from 44.76% to 31.86%; S30A70 and A100 were statistically equivalent for ADF. ADL also declined with alfalfa inclusion, though S70A30, S50A50, S30A70, and A100 were all comparable and

significantly lower than S100. Crude ash showed the inverse pattern, being similar across sorghum-dominant treatments (8.31-9.47%) but rising sharply to 12.81% in A100.

Table 1. Mean values and significance groups for silage fermentation and nutritive traits of sorghum-alfalfa mixtures

Trait	100% Sorghum	70% Sorghum + 30% Alfalfa	50% Sorghum + 50% Alfalfa	30% Sorghum + 70% Alfalfa	100% Alfalfa	F value
pH	3.73c	3.95c	3.96c	4.24b	5.19a	47.72**
Dry Matter (%)	24.94b	25.07b	25.21ab	25.44ab	25.66a	3.59*
Crude Protein (%)	7.86e	12.22d	13.07c	14.98b	16.56a	594.78**
Crude Fiber (%)	30.05a	25.38b	24.77b	22.60c	19.11d	87.13**
Crude Ash (%)	8.31b	8.66b	8.92b	9.47b	12.81a	21.34**
NDF (%)	61.19a	47.19b	44.47c	43.50c	40.98d	254.22**
ADF (%)	44.76a	41.61b	34.06c	32.56d	31.86d	151.28**
ADL (%)	3.25a	2.39b	2.22b	2.17b	1.99b	9.08**

*Means in the same row followed by different letters differ significantly. **: $p<0.01$; *: $p<0.05$.*

DISCUSSION

The monotonic increase in silage pH with rising alfalfa proportion is a direct consequence of alfalfa's high buffering capacity, which arises primarily from its protein content, free amino acids, and cation-bound organic acids. Buffering capacity quantifies the resistance of a substrate to pH change per unit of acid added; in legumes such as alfalfa, this resistance is substantially greater than in cereals, meaning that LAB must produce considerably more lactic acid to achieve an equivalent pH reduction. Pure sorghum silage at pH 3.73 demonstrated vigorous LAB activity facilitated by the crop's abundant WSC, whereas pure alfalfa silage at pH 5.19 reflects a fermentation environment where acid production was insufficient to overcome the buffering load -- a pattern consistent with the findings of Chen et al. (2018b) and Tao et al. (2019). At pH values above approximately 4.5-5.0, conditions remain permissive for clostridial activity and undesirable proteolysis, which can elevate ammonia nitrogen and non-protein nitrogen fractions and reduce the feed value of the silage. The statistical equivalence of pH among S100, S70A30, and S50A50 (all approximately 3.73-3.96) indicates that sorghum inclusions of 50% or above are sufficient to maintain acidification within a range associated with stable, high-quality lactic acid fermentation.

The narrow and statistically weak gradient in dry matter content (24.94-25.66%) across mixture ratios reflects the similarity in moisture level of both crops at their respective recommended harvest stages and suggests that DM content per se is not a major differentiating factor between these mixtures under the conditions of this study. Nevertheless, even these modest differences reached statistical significance ($p<0.05$), confirming sensitivity of DM to species composition.

The steep and highly significant increase in CP from 7.86% (S100) to 16.56% (A100) directly illustrates alfalfa's capacity to address the protein deficiency of sorghum silage. For high-producing dairy cows or growing beef cattle, the difference between approximately 8% CP (pure sorghum) and 13-15% CP (S50A50 or S30A70) has direct practical implications for concentrate protein savings and ration formulation costs. Importantly, the S50A50 and S30A70 mixtures achieved CP levels of 13.07 and 14.98%, respectively, representing a 66-90% increase over pure sorghum silage, while maintaining silage pH below 4.25 -- a range still considered adequate for preservation. This complementarity aligns with observations from co-ensiling alfalfa with other high-WSC crops: increases in legume proportion reliably enhance CP while the cereal component maintains fermentation quality (Dawuti et al., 2024; Sun et al., 2023; Tao et al., 2019).

The pronounced decrease in NDF, ADF, and crude fiber with increasing alfalfa content reflects the structural anatomy of sorghum stems, which accumulate larger quantities of cellulose and hemicellulose per unit DM than alfalfa at comparable growth stages. The extremely high NDF of pure sorghum silage (61.19%) would constrain voluntary dry matter intake in ruminants, as NDF is the primary predictor of

physical fill in the rumen. Reduction of NDF to 43.50-44.47% in the S30A70 and S50A50 mixtures could meaningfully increase potential intake relative to pure sorghum silage (Chen et al., 2018b). Similarly, ADF values above 40% as seen in S100 and S70A30 are associated with reduced energy digestibility, and the lower ADF in alfalfa-rich mixtures partially offsets the negative fermentation effects of higher pH. ADL declined significantly from S100 (3.25%) to mixed treatments (2.17-2.39%), indicating that lignin-mediated constraints on cell-wall digestibility are attenuated by alfalfa inclusion. The sharp rise in crude ash in A100 (12.81%) compared to sorghum-dominant treatments (8.31-9.47%) is consistent with alfalfa's well-known richness in calcium, potassium, and magnesium, though high ash dilutes the organic matter fraction and thus slightly reduces the net energy concentration of the silage.
Taken together, the S50A50 and S30A70 mixtures represent the most practically balanced options: they sustain a fermentation pH below 4.25, achieve CP values of 13-15% that can substantially reduce concentrate protein requirements, and reduce NDF and ADF to levels more compatible with adequate ruminant intake and digestibility compared to pure sorghum silage. These results are in good agreement with the recommendation by Chen et al. (2018b) that a sorghum-to-alfalfa ratio around 75:25 to 50:50 on a fresh weight basis offers the best compromise between fermentation efficiency and nutritive value in mixed silages.

CONCLUSION

This study showed that sorghum-alfalfa mixture ratio markedly influences both fermentation characteristics and chemical composition of the resulting silage. Increasing the sorghum proportion progressively lowered pH and raised cell-wall fractions (NDF, ADF, ADL) and crude fiber, while increasing the alfalfa proportion elevated crude protein and crude ash. Dry matter content was affected to a lesser degree than the other traits. Pure sorghum silage achieved the most favorable fermentation (pH 3.73) but provided inadequate protein (7.86%), whereas pure alfalfa silage delivered the highest protein (16.56%) and ash content (12.81%) at the cost of poor acidification (pH 5.19). The 50% Sorghum + 50% Alfalfa and 30% Sorghum + 70% Alfalfa mixtures provided the most balanced combination of adequate fermentation stability and improved nutritive value, and are recommended as practical alternatives for ruminant feeding programs aimed at boosting roughage protein content without sacrificing silage preservation. Future research should evaluate aerobic stability, organic acid profiles, and in vivo animal performance responses to these mixture ratios to fully characterize their feeding value.

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FARKLI MISIR (ZEA MAYS L.) VE SOYA (GLYCINE MAX L.) KARIŞIM ORANLARININ SİLAJ KALİTESİ VE BESİN İÇERİĞİ ÜZERİNE ETKİLERİ

EFFECTS OF DIFFERENT MAIZE (ZEA MAYS L.) AND SOYBEAN (GLYCINE MAX L.) MIXTURE RATIOS ON SILAGE QUALITY AND NUTRIENT CONTENT

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ÖZET
Bu çalışma, mısır ve soyanın farklı oranlarda karıştırılmasıyla hazırlanan silajların fermantasyon ve besin özelliklerinin belirlenmesi amacıyla yürütülmüştür. Denemede beş karışım oranı (%100 Soya; %70 Mısır + %30 Soya; %50 Mısır + %50 Soya; %30 Mısır + %70 Soya; %100 Mısır) tesadüf parselleri deneme desenine göre üç tekerrürlü olarak düzenlenmiştir. Silaj örneklerinde pH, kuru madde, ham protein, ham selüloz, ham kül, NDF, ADF ve ADL analizleri yapılmıştır. Elde edilen veriler tek yönlü varyans analizine (ANOVA) tabi tutulmuş ve ortalamalar Duncan çoklu karşılaştırma testi ile gruplandırılmıştır. Karışım oranları arasındaki farklar incelenen tüm özellikler bakımından istatistiksel olarak önemli ($p<0,01$) bulunmuştur. Mısır oranı arttıkça silaj pH'sı 5,49'dan 4,00'a düşmüş, bu da mısırın silaj fermantasyonunu iyileştirdiğini göstermiştir. Kuru madde içeriği en yüksek %100 mısır (%33,56), en düşük %100 soya (%24,53) silajında belirlenmiştir. Buna karşılık ham protein içeriği soya oranıyla doğru orantılı olarak artmış; en yüksek değer %100 soya (%13,52), en düşük değer %100 mısır (%8,90) silajında tespit edilmiştir. Hücre çeperi bileşenleri (NDF, ADF, ADL) ile ham selüloz ve ham kül içerikleri soya oranı arttıkça yükselmiştir. Sonuç olarak, mısırın fermantasyon kalitesini artırmadaki (düşük pH, yüksek kuru madde) etkisi ile soyanın protein içeriğini yükseltmedeki etkisi birlikte değerlendirildiğinde, mısır-soya karışımlarının kaliteli silaj üretiminde her iki bitkinin üstün yönlerini birleştirebileceği ve özellikle %50 Mısır + %50 Soya ile %70 Mısır + %30 Soya oranlarının dengeli bir alternatif oluşturabileceği sonucuna varılmıştır.
Anahtar kelimeler: Silaj, Mısır (*Zea mays* L.), Soya (*Glycine max* L.), Karışım oranı, Fermantasyon kalitesi, Besin içeriği

ABSTRACT
This study aimed to determine the fermentation and nutrient characteristics of silages prepared by mixing maize and soybean at different ratios. In the experiment, five mixture ratios (100% Soybean; 70% Maize + 30% Soybean; 50% Maize + 50% Soybean; 30% Maize + 70% Soybean; 100% Maize) were arranged according to a randomized plots design with three replications. pH, dry matter, crude protein, crude fiber, crude ash, NDF, ADF and ADL analyses were carried out on the silage samples. The data obtained were subjected to one-way analysis of variance (ANOVA), and the means were grouped using Duncan's multiple comparison test. The differences among the mixture ratios were found to be statistically significant ($p<0.01$) for all the traits examined. As the maize ratio increased, silage pH decreased from 5.49 to 4.00, indicating that maize improved silage fermentation. The dry matter content was highest in the 100% maize (33.56%) and lowest in the 100% soybean (24.53%) silage. In contrast, crude protein content increased in direct proportion to the soybean ratio; the highest value was determined in the 100% soybean (13.52%) and the lowest in the 100% maize (8.90%) silage. Cell wall components (NDF, ADF, ADL) as well as crude fiber and crude ash contents increased as the soybean

ratio increased. In conclusion, when the effect of maize in enhancing fermentation quality (low pH, high dry matter) and that of soybean in increasing protein content are evaluated together, it was concluded that maize-soybean mixtures can combine the superior aspects of both crops in the production of high-quality silage, and that the 50% Maize + 50% Soybean and 70% Maize + 30% Soybean ratios in particular may constitute a balanced alternative.
Keywords: Silage, Maize (*Zea mays* L.), Soybean (*Glycine max* L.), Mixture ratio, Fermentation quality, Nutrient content

INTRODUCTION

Maize (*Zea mays* L.) silage is one of the most widely used roughage sources in ruminant nutrition worldwide, prized for its high energy density, palatability, ease of ensiling, and consistent year-round availability. The high content of water-soluble carbohydrates (WSC) in maize facilitates rapid lactic acid fermentation, resulting in a stable, low-pH silage that preserves nutritional quality over extended storage periods (Cui et al., 2022; Jiao et al., 2025). Various processing approaches, including whole-plant harvesting and mechanical treatments such as shredlage, have been shown to further improve starch availability and fibre digestibility of maize silage, thereby enhancing its energy value for ruminants (Jancik et al., 2022).

Despite these advantages, the principal nutritional limitation of maize silage is its relatively low crude protein (CP) content, typically ranging from 7 to 9% on a dry matter (DM) basis. This level is insufficient to meet the requirements of high-producing dairy cows or rapidly growing beef cattle, and therefore necessitates the use of costly protein supplements or concentrate feeds, increasing the overall cost of animal production (Demirel et al., 2003; Spore et al., 2021). Several strategies have been explored to address this constraint, including the use of urea supplementation, alternative high-protein forages such as forage rape (*Brassica napus* L.) silage, and the selection of maize varieties with intrinsically higher protein content (Jiao et al., 2025; Spore et al., 2021; Zhou et al., 2021). However, these approaches either add cost or are limited in practical scalability.

Soybean (*Glycine max* L. Merr.) is among the most protein-rich annual forage crops, with shoot biomass containing 13-18% CP and a well-balanced amino acid profile that complements the nutritional gaps of cereal silages. However, ensiling pure soybean presents considerable technical difficulties. Its low DM content, limited WSC concentration, and high buffering capacity collectively inhibit lactic acid bacterial (LAB) activity, thereby slowing pH decline and increasing the risk of clostridial fermentation and butyric acid accumulation (Bolson et al., 2021; Horiguchi and Takahashi, 2007). These fermentation defects reduce palatability and dry matter intake by animals, and can result in substantial nutrient losses during storage. Various interventions, including inoculation with Lactiplantibacillus plantarum and the use of epiphytic LAB populations, have been investigated to improve soybean silage quality, with promising but variable results depending on the conditions (Jin et al., 2024; Meng et al., 2025; Wang et al., 2026).

Co-ensiling maize with soybean has therefore emerged as a rational and practical strategy that leverages the complementary strengths of both crops. Maize provides the readily fermentable carbohydrates and dry matter needed for stable lactic acid fermentation, while soybean contributes protein and essential minerals, thereby improving the overall nutritive value of the resulting silage. Research has demonstrated that maize-soybean mixed silages can achieve CP values approximately 40% higher than pure maize silage, while maintaining fermentation profiles, including pH and organic acid composition, comparable to maize-only silage (Bolson et al., 2021; Meng et al., 2022). Studies evaluating the effects of LAB inoculants in mixed silages further confirm that appropriate microbial supplementation can enhance aerobic stability, reduce undesirable fermentation products, and improve protein preservation in these systems (Cayiroglu, 2025; Meng et al., 2025). Importantly, the mixture ratio of maize to soybean is a critical variable: increasing the soybean proportion raises CP and mineral content but also elevates cell-wall fractions (NDF, ADF, ADL), which may limit ruminal digestibility and reduce net energy availability (Carpici, 2016; Meng et al., 2022). At the same time, an excessive reduction in maize proportion can compromise fermentation quality by lowering the WSC-to-buffering-capacity ratio of the mixture (Bolson et al., 2021; Cheng et al., 2020).

Despite these insights, a systematic evaluation of the full range of binary mixture ratios from pure maize to pure soybean under controlled micro-silo conditions, encompassing both fermentation parameters and a comprehensive chemical composition profile including cell-wall fractions, remains limited in the

literature. Defining the quantitative relationships between mixture composition and silage quality across this entire spectrum is essential for evidence-based formulation of mixed silage programs. Therefore, this study aimed to determine the effects of five maize-soybean mixture ratios (100% Maize; 70% Maize + 30% Soybean; 50% Maize + 50% Soybean; 30% Maize + 70% Soybean; 100% Soybean) on silage pH, dry matter, crude protein, crude fiber, crude ash, NDF, ADF, and ADL, and to identify the mixture ratio that most effectively balances fermentation quality with nutritive value for use in ruminant feeding programs.

MATERIALS and METHODS

Maize (*Zea mays* L.) was harvested at the milk-dough stage and soybean (*Glycine max* L.) at the lower-pod filling stage, both recognized as the optimal harvest windows for silage production. Five mixture ratios on a fresh weight basis were prepared: 100% Maize (M100), 70% Maize + 30% Soybean (M70S30), 50% Maize + 50% Soybean (M50S50), 30% Maize + 70% Soybean (M30S70), and 100% Soybean (S100). Freshly harvested material was chopped to a particle length of approximately 1-2 cm, weighed, and blended homogeneously to achieve the target ratios. Approximately 2 kg of each mixture was compacted into air-tight polyethylene micro-silo bags, heat-sealed to exclude air, and stored at 24 ± 2 °C in the dark for 60 days. Each treatment was replicated three times, giving 15 micro-silos in total. Upon opening, silage pH was determined by homogenising approximately 30 g of fresh silage in 270 mL of distilled water for 30 seconds, filtering the suspension, and measuring with a calibrated digital pH meter (Mettler Toledo Seven Compact, Switzerland). For dry matter (DM) determination, approximately 500 g sub-samples were oven-dried at 70 °C until constant weight was reached; dried material was subsequently ground through a 1 mm screen. Crude protein (CP; Kjeldahl N × 6.25) and crude ash (CA; muffle furnace at 550 °C) were determined according to AOAC (1990). Crude fiber (CF) was determined using standard sequential acid-alkali extraction. Neutral detergent fiber (NDF; with sodium sulphite and heat-stable amylase), acid detergent fiber (ADF), and acid detergent lignin (ADL) were analysed using an ANKOM 200 Fiber Analyzer (ANKOM Technology, NY, USA) following ANKOM Tech Methods (2017). All results are expressed on a DM basis.

The experimental data were subjected to one-way analysis of variance (ANOVA) using the SAS statistical software package (SAS, 1999) based on a completely randomized design with three replications. Mixture ratio was treated as the treatment factor. When the F-test indicated a statistically significant difference among treatments, means were separated using the Least Significant Difference (LSD) test at the $p<0.05$ and $p<0.01$ significance levels.

RESULTS

The differences among the five maize-soybean mixture ratios were statistically significant ($p<0.01$) for all traits examined (Table 1). Silage pH decreased progressively as the maize proportion increased, ranging from 5.49 in S100 to 4.00 in M100, while dry matter (DM) content followed the inverse trend, rising from 24.53% in S100 to 33.56% in M100. The M50S50 and M30S70 mixtures were statistically comparable in DM (30.59% and 31.02%, respectively), both approaching the recommended threshold for minimising effluent losses. Crude protein (CP) declined monotonically with increasing maize proportion, from 13.52% in S100 to 8.90% in M100, with each treatment forming a distinct statistical group. Crude ash (CA) showed the same directional response, falling from 13.60% (S100) to 4.46% (M100). Cell-wall fractions and crude fiber increased proportionally with higher soybean inclusion: NDF ranged from 33.63% (M100) to 52.83% (S100), ADF from 17.99% to 28.76%, and CF from 16.62% to 27.45%. ADL exhibited a non-monotonic pattern, with M100 (2.98%) and M50S50 (2.92%) being statistically equivalent, while M30S70 recorded the lowest value (2.39%).

Table 1. Mean values and significance groups for silage quality and nutritive traits of maize-soybean mixtures

Trait	100% Soybean	70% Maize + 30% Soybean	50% Maize + 50% Soybean	30% Maize + 70% Soybean	100% Maize	F value
pH	5.49a	4.56b	4.33bc	4.23cd	4.00d	38.42**
Dry Matter (%)	24.53d	27.61c	30.59b	31.02b	33.56a	21.13**
Crude Protein (%)	13.52a	12.58b	11.45c	10.65d	8.90e	144.14**

Trait	100% Soybean	70% Maize + 30% Soybean	50% Maize + 50% Soybean	30% Maize + 70% Soybean	100% Maize	F value
Crude Fiber (%)	27.45a	25.15b	19.66c	17.85d	16.62d	74.63**
Crude Ash (%)	13.60a	11.42b	7.23c	5.36d	4.46e	988.97**
NDF (%)	52.83a	45.70b	42.33c	37.60d	33.63e	103.20**
ADF (%)	28.76a	27.52b	20.39c	18.69d	17.99e	539.34**
ADL (%)	3.90a	3.49b	2.92c	2.39d	2.98c	71.42**

*Means in the same row followed by different letters differ significantly. **: p<0.01.*

DISCUSSION

The progressive decrease in silage pH with increasing maize proportion reflects the greater availability of WSC in maize grain, which provides a readily accessible substrate for lactic acid bacteria (LAB). Rapid conversion of WSC to lactic acid drives the pH decline essential for preserving nutritional quality and suppressing undesirable microbial activity. Pure soybean silage at pH 5.49 is consistent with inadequate acidification arising from the inherently low WSC-to-buffering-capacity ratio of legumes; at this pH level, conditions remain conducive to clostridial activity and butyric acid production, which degrade both fermentation quality and feed palatability (Bolson et al., 2021; Cheng et al., 2020; Horiguchi and Takahashi, 2007). Maize inclusion at or above 50% brought silage pH below 4.40, approaching the range considered optimal for lactic acid fermentation in cereal-based silages (3.8-4.2), in agreement with Carpici (2016) and Meng et al. (2022).

The DM content of S100 (24.53%) falls below the generally recommended minimum of approximately 25-28% for stable silage; at such moisture levels, the risk of effluent formation and leaching of soluble nutrients during ensiling increases substantially (Cheng et al., 2020; Demirel et al., 2003). Mixtures containing at least 50% maize raised DM above 28%, offering a meaningful improvement in storage stability. The fact that M50S50 and M30S70 did not differ statistically in DM despite differing in mixture ratio suggests a plateauing effect at intermediate compositions, which may be relevant when selecting ratios to optimise both fermentation and protein content simultaneously.

The linear decline in CP with increasing maize proportion confirms that soybean inclusion is an effective means of elevating the protein value of maize silage. The 3-4 percentage unit increase in CP achieved in M70S30 and M50S50 relative to M100 is nutritionally significant in the context of ruminant feeding: it can substantially reduce the quantity of protein concentrate required to balance a ration based predominantly on cereal silage, with corresponding economic benefits for farm operations (Demirel et al., 2003; Owens et al., 1970). The reduction in CA from soybean-rich to maize-dominant mixtures is also nutritionally favourable, as lower ash content is associated with higher net energy density of the feed.

Elevated NDF, ADF, and ADL in soybean-rich silages reflect the more lignified stem anatomy of soybean relative to maize at comparable growth stages. Lignin forms covalent ester and ether bonds with structural carbohydrates, restricting the access of ruminal microorganisms and enzymes to cellulose and hemicellulose, and thereby imposing a direct ceiling on cell-wall digestibility (Kornegay, 1981; Zeoula et al., 2018). The NDF of 52.83% and ADF of 28.76% in S100 would impose constraints on voluntary feed intake and digestibility in ruminants that partially offset the protein advantage of high-soybean mixtures. The non-monotonic ADL response, where M100 and M50S50 were statistically equivalent and M30S70 had the lowest value, may reflect interactions between stem-to-leaf ratio, botanical maturity at harvest, and the differential lignification dynamics of the two species at their respective harvest stages; this pattern warrants further investigation in future studies.

Taken together, these results indicate that M70S30 and M50S50 offer the most advantageous combination of silage characteristics: acceptable fermentation pH (4.33-4.56), DM above the minimum stability threshold (>27%), CP elevated by 3-4 percentage units above pure maize silage, and cell-wall fractions that remain within ranges compatible with adequate ruminal fibre digestion. These findings are consistent with the recommendations of Bolson et al. (2021) and Carpici (2016), who suggest that a minimum of 50% maize in the mixture is necessary to secure fermentation quality, and with Meng et al. (2022), who reported optimal fermentation characteristics at intermediate soybean proportions in strip-intercropped maize-soybean systems.

CONCLUSION

This study demonstrated that co-ensiling maize and soybean effectively integrates the fermentation stability of maize with the superior protein content of soybean. Pure maize silage provided the best fermentation characteristics (pH 4.00, DM 33.56%) but the lowest CP (8.90%), whereas pure soybean silage delivered the highest CP (13.52%) at the expense of inadequate fermentation (pH 5.49, DM 24.53%) and elevated cell-wall fractions that would constrain ruminal digestibility. The 70% Maize + 30% Soybean and 50% Maize + 50% Soybean mixtures achieved the most balanced profiles across all traits evaluated and are recommended as practical alternatives in ruminant feeding programs aimed at improving roughage protein content while maintaining silage fermentation quality. To fully validate the practical utility of these mixtures, future research should assess in vivo dry matter and fibre digestibility, aerobic stability during feed-out, and direct effects on animal performance including milk yield and daily live weight gain.

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PRODUCTION, PARTIAL PURIFICATION, AND BIOCHEMICAL CHARACTERIZATION OF AMYLASE FROM BACİLLUS SUBTİLİS N28

BACİLLUS SUBTİLİS N28'DEN AMİLAZIN ÜRETİMİ, KISMİ SAFLAŞTIRILMASI VE BİYOKİMYASAL KARAKTERİZASYONU

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ÖZET
Mikrobiyal enzimler, çevre dostu, sürdürülebilir ve ekonomik olarak uygulanabilir süreçleri desteklemedeki yeni uygulamaları nedeniyle çeşitli endüstrilerde giderek artan bir talep görmektedir. α-amilaz, nişastadaki α-1,4-glukozidik bağların hidrolizini katalize ederek oligosakkarit karışımı üreten önemli bir enzim grubudur. Gıda, bira, kağıt, deterjan, tekstil ve tıp endüstrileri de dahil olmak üzere birçok sektörde yaygın olarak kullanılmaktadır. Bunun yanı sıra son yıllarda geliştirilmiş aktivite, termal kararlılık, geniş pH profili ve substrat özgüllüğü gibi istenen özelliklere sahip amilazlar, endüstrinin büyük bir ilgisini çekmiştir. Bu nedenle farklı endüstriyel uygulamalara uygun yeni amilaz üreten mikrobiyal suşların izolasyonuna ve optimizasyonuna sürekli bir ilgi bulunmaktadır. Bu kapsamda mevcut çalışmada, maruldan izole edilen *Bacillus subtilis* N28 suşunun amilaz üretme yeteneği kalitatif ve kantitatif olarak test edildi, amilaz enzimi amonyum sülfat çöktürmesi ile kısmi olarak saflaştırıldı ve biyokimyasal olarak karakterize edildi. Suşun amilaz aktivitesi kısmi saflaştırma sonrası 30,2 U/mL olarak, protein konsantrasyonu ise 97,7 µg/mL olarak tespit edildi. Enzimin maksimum aktivite gösterdiği sıcaklık ve pH değerleri sırasıyla 40 °C ve pH 5.0 olarak belirlendi. K_m ve V_{max} değerleri ise sırasıyla 2,77 mg/mL ve 25,16 µmol/dk olarak saptandı. Elde edilen sonuçlar *B. subtilis* N28'den kısmi olarak saflaştırılan amilazın asidik koşullarda yürütülen ve yüksek sıcaklık gerektirmeyen endüstriyel uygulamalar için kullanım potansiyeline sahip olduğunu göstermektedir.
Anahtar kelimeler: Bakteri, *Bacillus*, enzim, amilaz, nişasta

ABSTRACT
Microbial enzymes are seeing growing demand across various industries due to their new applications in supporting environmentally friendly, sustainable, and economically viable processes. α-amylase is an important group of enzymes that catalyzes the hydrolysis of α-1,4-glucosidic bonds in starch, producing a mixture of oligosaccharides. It is widely used in many sectors, including the food, brewing, paper, detergent, textile, and medical industries. In addition, amylases developed in recent years that possess desirable properties such as enhanced activity, thermal stability, a broad pH profile, and substrate specificity have attracted significant interest from the industry. For this reason, there is ongoing interest in the isolation and optimization of new microbial strains that produce amylase suitable for various industrial applications. In this context, the present study qualitatively and quantitatively tested the amylase-producing ability of the *Bacillus subtilis* N28 strain isolated from lettuce; the amylase enzyme was partially purified by ammonium sulfate precipitation and biochemically characterized. The amylase activity of the strain was determined to be 30.2 U/mL after partial purification, while the protein concentration was found to be 97.7 µg/mL. The temperature and pH at which the enzyme exhibited maximum activity were determined to be 40 °C and pH 5.0, respectively. The K_m and V_{max} values were determined to be 2.77 mg/mL and 25.16 µmol/min, respectively. The results obtained indicate that the

amylase partially purified from *B. subtilis* N28 has the potential for use in industrial applications conducted under acidic conditions that do not require high temperatures.
Keywords: Bacteria, *Bacillus*, enzyme, amylase, starch

INTRODUCTION

Microbial enzymes, which have replaced traditional chemical methods in industrial processes in recent years, are in high demand because they reduce the need for harsh conditions such as high pressure and temperature, are eco-friendly and sustainable, and offer high economic efficiency (Far et al., 2020; Farooq et al., 2021; Abo-Kamer et al., 2023). Among these industrial biocatalysts, α-amylases (EC 3.2.1.1) which form the basis of starch processing technologies—catalyze the production of mixtures of glucose, maltose, and oligosaccharides by specifically hydrolyzing internal α-1,4-glucosidic bonds in starch and other polysaccharides (Paul et al., 2021; Oyenado and Omoruyi 2024).

Alpha-amylases play critical roles across a very wide industrial spectrum today (Far et al., 2020; Oyenado and Omoruyi 2024). While widely used in the food and baking industries for dough processing, increasing bread volume, delaying staling, extending shelf life, and clarifying beverages, it offers an ecological advantage in the detergent industry by enabling the effective removal of starch-based stains under low-temperature and mild conditions (Far et al., 2020; Taheri-Kafrani et al., 2021; de Souza et al., 2024). It plays an indispensable role in the textile industry by removing sizing agents applied to yarns prior to weaving without damaging the fibers; in the paper and pulp industry by enhancing paper strength and surface quality; and in bioethanol production by liquefying and saccharifying starch (Far et al., 2020; Paul et al., 2021; Farooq et al., 2021).

On an industrial scale, α-amylase is obtained from plant, animal, and microbial sources (Paul et al., 2021). However, microbially derived amylases are predominantly preferred in industrial production today due to their rapid proliferation capacities, high enzyme secretion potentials, and the ease of optimizing culture conditions (Far et al., 2020; Niyonzima et al., 2020). Bacteria of the genus Bacillus (e.g., *B. subtilis*, *B. amyloliquefaciens*, *B. licheniformis*), in particular, are the most preferred microorganisms in industrial applications due to their ability to produce large quantities of stable amylase enzymes extracellularly (Far et al., 2020; Zalila-Kolsi et al., 2023). The enzyme characteristics required by each industrial process vary. Accordingly, the isolation and purification of novel amylase-producing microbial strains derived from nature and agricultural matrices and possessing unique properties as well as the determination of their biochemical characteristics, are of great importance from a biotechnological perspective (Far et al., 2020; Shad et al., 2023; Mahfudz et al., 2024).

In this study, the amylase-producing capability of the *B. subtilis* N28 strain, isolated from lettuce, was tested both qualitatively and quantitatively. The amylase enzyme produced by the strain was partially purified via ammonium sulfate precipitation. The purified amylase was biochemically characterized by determining its optimal temperature and pH, as well as its kinetic parameters (K_m and V_{max}), and its potential industrial applications were evaluated.

MATERIALS AND METHODS

Bacterial Strain

The *B. subtilis* N28 strain used in this study is stored at -80 °C in a stock solution containing 50% glycerol in the culture collection of N. Dikbaş at the Department of Agricultural Biotechnology, Faculty of Agriculture, Atatürk University.

Qualitative and Quantitative Determination of Amylase Production by the Strain

The amylase-producing ability of *B. subtilis* N28 was first tested qualitatively on Nutrient Agar containing 1% soluble starch. The strain was inoculated into the starch agar medium and incubated at 28 °C for 48 hours. After incubation, an iodine solution was added to the Petri dish and allowed to stand for 5 minutes. The formation of a clear zone around the colony was considered a positive indicator of amylase production. The amylolytic index (AI) was determined by calculating the ratio of the zone diameter to the colony diameter.

The quantitative amylase activity of the strain was tested using the dinitrosalicylic acid (DNS) method, which measures the amount of reducing sugars released into the medium during starch hydrolysis. *B. subtilis* N28 was incubated at 28 °C for 24 hours in Nutrient Broth containing 1% soluble starch. After incubation, the cultures were centrifuged at 7,000 rpm for 10 minutes at 4 °C, and the supernatant was

used to test amylase activity. An enzyme solution (0.5 mL) and a substrate consisting of 1% (w/v) soluble starch (in 20 mM potassium phosphate buffer, pH 6.5) (500 µL) were reacted at 50 ± 1 °C for 10 minutes. The enzymatic reaction was stopped by adding 1 mL of DNS reagent and boiled in a hot water bath for 10 minutes to facilitate color development. The tubes were cooled, and absorbance was measured at 540 nm. In the blank sample, distilled water was used instead of the enzyme.

Partial Purification of Amylase

The ammonium sulfate precipitation method was used for the partial purification of amylase from *B. subtilis* N28. The strain was incubated at 28 °C for 48 hours in NB medium containing 1% soluble starch. It was then centrifuged at 7,000 rpm for 10 minutes at +4 °C, and the cell-free supernatant was used for partial purification (Dikbaş et al., 2023). The partial purification process was carried out in the 0–80% range, and the precipitate obtained from each fraction after purification was dissolved in 20 M sodium phosphate buffer (pH 6.5) and stored at +4 °C for the determination of activity and protein concentration. Protein concentration was determined using the Bradford method (Bradford 1976).

The Effect of Temperature on Amylase Activity

A partially purified amylase enzyme was reacted with a substrate consisting of a 1% (w/v) starch solution (in a 20 mM potassium phosphate buffer at pH 6.5) at different temperatures (10–90 °C) in 10 °C intervals, and enzyme activity was measured using the DNS method.

The Effect of pH on Amylase Activity

The partially purified amylase enzyme was reacted with substrates consisting of 1% (w/v) soluble starch adjusted to different pH values (2–11), and enzyme activity was measured using the DNS method.

Determination of Km and Vmax Values

Amylase activity was measured using the DNS method at different substrate concentrations (1, 1.5, 2, 2.5, 3, 3.5, and 4 mg/mL), and K_m and V_{max} values were determined by plotting a Lineweaver-Burk graph (Demir et al. 2018).

FINDINGS AND DISCUSSION

α-amylases are important biocatalysts in the starch hydrolysis process, with applications in the detergent, food, paper, ethanol production, and textile industries for many years. Due to their diverse applications, the continuously expanding global market has driven both industry and academia in this field to isolate and develop new and improved versions of amylase (Ashok et al., 2024; Suthar et al., 2024).

In this study, the amylase production of the *B. subtilis* N28 strain isolated from lettuce was tested both qualitatively and quantitatively, and it was determined that the strain is capable of producing amylase. The N28 strain formed a distinct zone by hydrolyzing starch on a starch agar medium (Figure 1), and its amylolytic index was determined to be 0.75. In addition, the amylase activity of the strain was measured at 38 U/mL in a liquid nutrient medium containing soluble starch. The results obtained support previous studies reporting the amylase-producing capabilities of *B. subtilis* strains isolated from various sources (Singh et al., 2022; Niyomukiza et al., 2023; Mahfudz et al., 2024; Kaur et al., 2026).

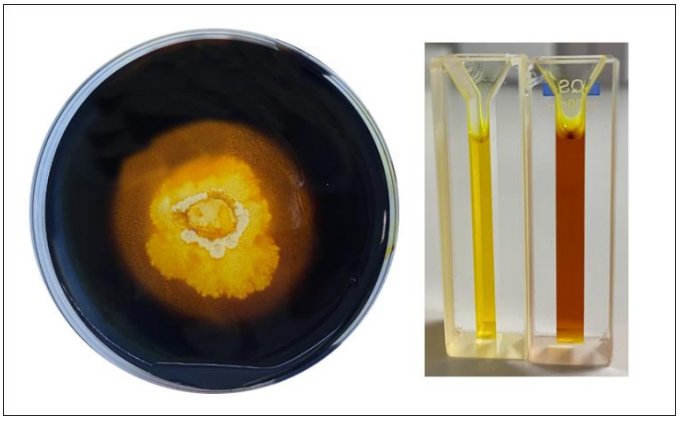


Figure 1. Qualitative and quantitative determination of amylase production by *B. subtilis* N28

Ammonium sulfate is widely used in enzyme precipitation due to its properties, such as chemical inertness at different pH values, the ability to enhance enzyme stability, and the fact that it is more soluble and less expensive than other salts (Abo-Kamer et al., 2023). The amylase enzyme from *B. subtilis* N28 was partially purified in the range of 0–80% using ammonium sulfate precipitation, and the results are presented in Figure 2. The highest amylase activity and protein concentration were measured at 30.2 U/mL and 97.7 µg/mL, respectively, in the 40–60 purification range. Similarly, Elamary and Salem (2020) reported that the amylase activity of *B. subtilis* isolated from soil was 32.0 U/mL within an ammonium sulfate precipitation range of 45–85%.

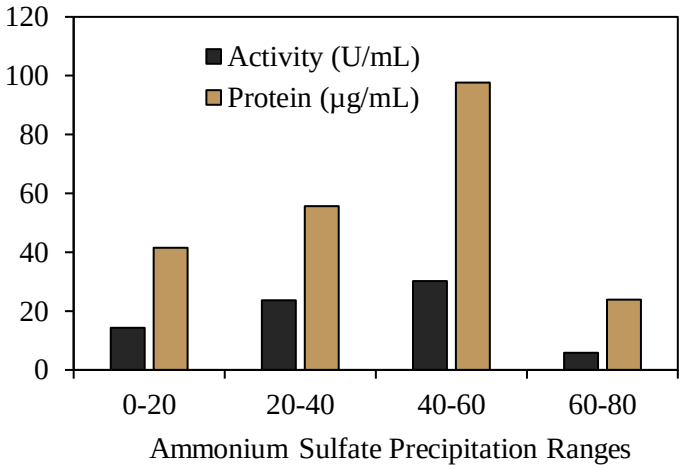


Figure 2. Enzyme activity and protein concentration of precipitates obtained at different ammonium sulfate saturation ranges

To determine the temperature at which the partially purified amylase exhibited optimal activity, enzyme activity was measured at temperatures ranging from 10 to 90 °C. The optimal temperature for amylase activity was determined to be 40 °C, and the results are presented in Figure 3. The enzyme retained approximately 60% of its maximum activity at temperatures ranging from 10 to 70 °C. In a parallel study, Zhang et al. (2024) reported that the *B. subtilis* AmyX8 amylase exhibited optimal activity at 40 °C. Similarly, the amylase purified from *B. licheniformis* VO1 exhibited its maximum activity at 45 °C (Akcan, 2021). The temperature at which the amylase from *Brachybacterium paraconglomeratum*, isolated from the wastewater of a textile factory, exhibited optimal activity was reported as 50 °C (Colak, 2022). In addition, the amylase enzyme purified from *B. stercoris* THS-K1, isolated from Tuva thermal springs, exhibited its highest catalytic activity at 50 ± 1 °C (Padia et al., 2025). Furthermore, the temperature at which the amylase purified from *B. cereus* GL2 exhibits optimal activity has been reported as 50 °C (Alhazmi and Alshehri, 2025). Furthermore, amylases exhibiting maximum activity at higher temperatures have been reported in the literature (Fincan et al., 2021; Kholikov et al., 2025).

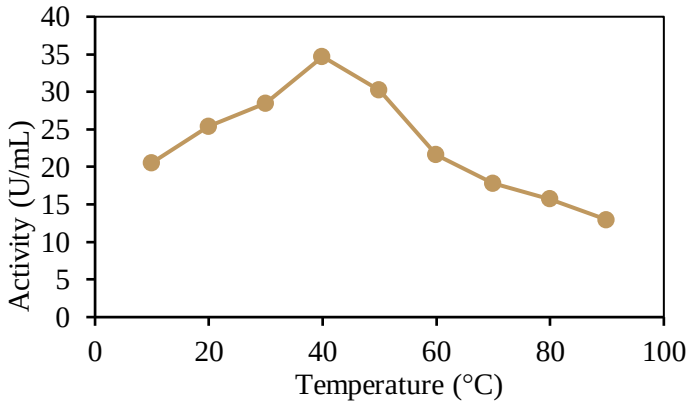


Figure 3. Effect of temperature on amylase activity

To determine the pH at which the partially purified amylase exhibited optimal activity, enzyme activity was measured at pH values ranging from 2.0 to 11.0. The optimal pH for amylase activity was determined to be 5.0 (37.1 U/mL), and the results are presented in Figure 4. The enzyme retained approximately 40% of its maximum activity at pH values ranging from 2 to 10. Consistent with the findings of this study, amylase purified from *B. siamensis* JJC33M exhibited maximum activity at pH 5.0 (Hernández-Heredia et al., 2025). Similarly, the optimal pH value for amylases purified from *Bacillus* sp. PM06 and *B. velezensis* MTCC13097 was reported as 5.5 (Rajesh and Gummadi, 2024; Bhimana and Ravindran, 2025). In contrast, amylases purified from *B. cereus* GL2 and *B. licheniformis* VO1 exhibited maximum activity at pH 6; those purified from *B. licheniformis* SO5 and *B. simplex* BCHCNZ282B exhibited maximum activity at pH 7; and amylases purified from *B. licheniformis* UDS-5 and *B. licheniformis* RA31 exhibited maximum activity at pH 8 (Akcan, 2021; Sharma et al., 2022; Suthar et al., 2024; Alhazmi and Alshehri, 2025; Aras et al., 2025; Karakoç et al., 2026).

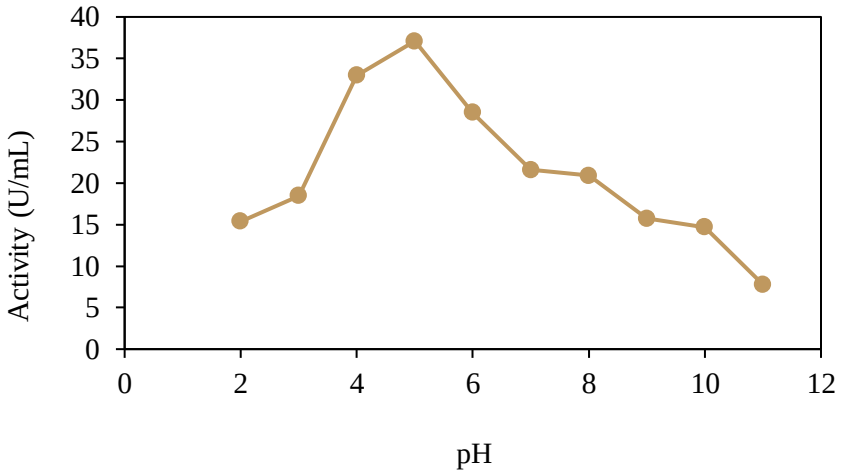


Figure 4. Effect of pH on amylase activity

To determine the effect of substrate concentration on amylase activity, kinetic parameters (K_m and V_{max}) were determined using different starch concentrations. The K_m value of the amylase partially purified from *B. subtilis* N28 was determined to be 2.77 mg/mL, and the V_{max} value was determined to be 25.16 µmol/min; the results are presented in Figure 5.

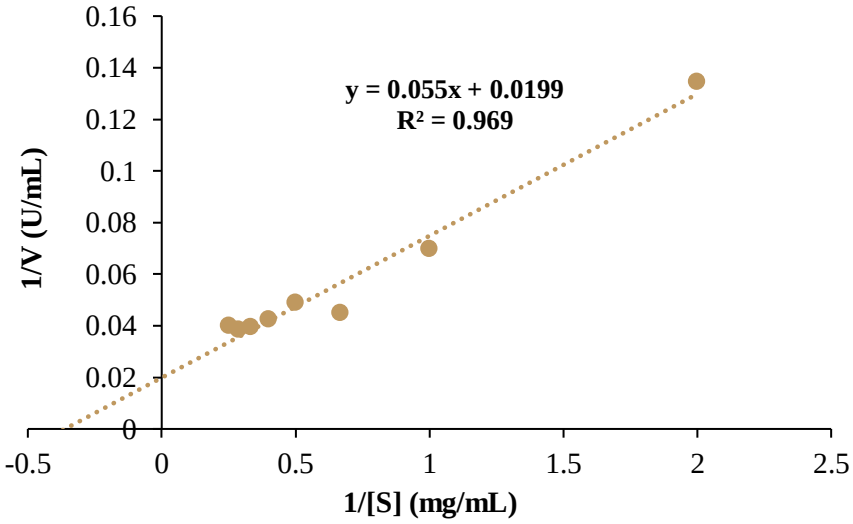


Figure 5. Lineweaver-Burk plot of partially purified amylase

When the K_m value obtained from this study was compared with the literature, it was found to be higher than that of amylases purified from *B. subtilis* (K_m = 6 mg/mL) and *Bacillus* sp. H7 (K_m= 5.1 mg/mL), but lower than that of amylases purified from *B. siamensis* JJC33M (K_m= 1.47 mg/mL) and *B. licheniformis* UDS-5 (K_m= 0.58 mg/mL) (Bandal et al., 2021; Suthar et al., 2024; Bibi et al., 2025; Hernández-Heredia et al., 2025). The findings indicate that the partially purified amylase exhibits good affinity for soluble starch.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the amylase enzyme from *B. subtilis* N28 was partially purified and biochemically characterized. The findings indicate that the enzyme has the potential for use in industrial applications that do not require acidic conditions or high temperatures. Furthermore, it is recommended that future studies focus on optimizing the production and purification conditions for *Bacillus* derived enzymes, testing the enzyme's stability at different temperatures and pH values, and conducting further characterization studies.

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LİSE ÖĞRENCİLERİNDE OYUN BAĞIMLILIĞI İLE SPORA KATILIM MOTİVASYONU ARASINDAKİ İLİŞKİNİN DEMOGRAFİK DEĞİŞKENLERE GÖRE İNCELENMESİ

EXAMINATION OF THE RELATIONSHIP BETWEEN GAMING ADDICTION AND MOTIVATION FOR SPORTS PARTICIPATION AMONG HIGH SCHOOL STUDENTS ACCORDING TO DEMOGRAPHIC VARIABLES

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ÖZET
Günümüzde dijital oyunların hemen hemen tüm yaş gruplarında yaygın olarak kullanılmasıyla birlikte, oyun bağımlılığı önemli bir araştırma konusu hâline gelmiştir. Oyun bağımlılığı, eğitim hayatını sürdüren öğrencilerin yalnızca akademik yaşamlarını değil, aynı zamanda fiziksel aktivite ve spora katılım motivasyonlarını da etkileyebilecek bir değişken olarak değerlendirilmektedir. Bu nedenle, bu çalışma lise öğrencilerinde oyun bağımlılığı ile spora katılım motivasyonu arasındaki ilişkinin incelenmesini ve bu değişkenlerin cinsiyet, yaş, sınıf düzeyi ve lisanslı sporcu olma durumuna göre farklılık gösterip göstermediğinin belirlenmesini amaçlamaktadır. Araştırmanın örneklemini, 148 erkek ve 171 kadın olmak üzere 15–18 yaş aralığında toplam 319 lise öğrencisi oluşturmuştur. Veriler, öğrencilerden Kişisel Bilgi Formu, Oyun Bağımlılığı Ölçeği ve Egzersize Katılım Motivasyonu Ölçeği kullanılarak toplanmıştır. Toplanan verilerin analizinde tanımlayıcı istatistikler, bağımsız örneklemler t-testi, ANOVA ve Pearson korelasyon analizi kullanılmıştır. Korelasyon analizinden elde edilen bulgulara göre, oyun bağımlılığı ile dışsal motivasyon arasında pozitif yönde anlamlı bir ilişki bulunurken, oyun bağımlılığı ile motivasyonsuzluk arasında negatif yönde anlamlı bir ilişki bulunmuştur. Ayrıca, içsel motivasyon ile dışsal motivasyon arasında pozitif yönde anlamlı bir ilişki tespit edilirken, dışsal motivasyon ile motivasyonsuzluk arasında negatif yönde anlamlı bir ilişki bulunmuştur. Bağımsız örneklemler t-testi ve ANOVA sonuçlarına göre, erkek öğrencilerin oyun bağımlılığı puanlarının kadın öğrencilere kıyasla anlamlı düzeyde daha yüksek olduğu belirlenmiştir. Araştırma sonucunda, lise öğrencilerindeki oyun bağımlılığının cinsiyet ve lisanslı sporcu olma durumuna göre farklılaştığı, motivasyon boyutlarındaki farklılıkların ise daha sınırlı olduğu tespit edilmiştir. Bu doğrultuda, okullarda dijital oyun kullanımına yönelik farkındalık artırıcı faaliyetlerin yürütülmesi ve öğrencilerin sağlıklı spor katılımı motivasyonunu destekleyen uygulamaların artırılması önerilmektedir.

Anahtar kelimeler: Oyun bağımlılığı, Spora katılım motivasyonu, İçsel motivasyon, Dışsal motivasyon, Motivasyonsuzluk, Lise öğrencileri.

ABSTRACT
With the widespread use of digital games across almost all age groups today, gaming addiction has become an important research topic. Gaming addiction is considered a variable that may affect not only the academic lives of students continuing their education but also their motivation to participate in physical activity and sports. Therefore, this study aims to examine the relationship between gaming addiction and motivation for sports participation among high school students and to determine whether these variables differ according to gender, age, grade level, and licensed athlete status. The sample of the study consisted of a total of 319 high school students aged 15–18 years, including 148 males and 171 females. Data were collected from the students using a Personal Information Form, the Gaming Addiction Scale, and the Exercise Participation Motivation Scale. Descriptive statistics, independent samples t-test, ANOVA, and Pearson correlation analysis were used in the analysis of the collected data. According to the findings obtained from the correlation analysis, a significant positive relationship was found between gaming addiction and extrinsic motivation, whereas a significant negative relationship was found between gaming addiction and amotivation. In addition, a significant positive relationship was identified between intrinsic motivation and extrinsic motivation, while a significant negative relationship was found between extrinsic motivation and amotivation. According to the results of the independent samples t-test and ANOVA, male students were found to have significantly higher gaming addiction scores than female students. As a result of the study, gaming addiction among high school students was found to differ according to gender and licensed athlete status, whereas differences in motivation dimensions were found to be more limited. Accordingly, it is recommended that awareness-raising activities regarding digital game use be carried out in schools and that practices supporting students' healthy motivation for sports participation be increased.
Keywords: Gaming addiction, Sports participation motivation, Intrinsic motivation, Extrinsic motivation, Amotivation, High school students.

GİRİŞ
Teknolojinin hızla gelişmesiyle birlikte dijital oyunlar, günümüzde sadece eğlence aracı olmaktan çıkmış ve bireylerin günlük yaşamında önemli bir yer edinerek sağlık sorunlarının görülmesine yol açabilmektedir (Demir vd., 2024). Nitekim, dijital oyunlar zaman içerisinde günün büyük bir bölümünü ele geçirmekte ve oyun bağımlılığı durumunun ortaya çıkmasına neden olmaktadır (Yalçın Irmak ve Erdoğan, 2015). Dijital oyun bağımlılığı, bireylerin oyun oynarken kendisini ve zamanı kontrol edememesi, oyun dışındaki aktivitelere ilgisiz kalması ve oyun oynamadığı süreçte yoksunluk hissetmesi gibi belirtilerle tanımlanmaktadır (Genc vd., 2024; Yalçın Irmak ve Erdoğan, 2015). Literatürde oyun bağımlılığının özellikle genç bireylerin, akademik başarılarının düşmesi, bilişsel işlevlerde bozulması, öz saygı, yaşam memnuniyeti ve sosyal desteğin azalması, uyku bozuklukları, depresyon ve anksiyetede artış gibi olumsuz sonuçlara neden olduğu ifade edilmektedir (Limone vd., 2023). Ancak, dijital oyunların olumsuz sonuçları olduğu kadar, sosyalleşme ve başarı hissi gibi olumlu çıktıların olduğu da görülmektedir (Genc vd., 2024). Yapılan bir meta analiz çalışmasında (Meng vd., 2022), küresel genel nüfusta oyun bağımlılığının yaygınlığı %6,04 olup, bu oran özellikle erkeklerde daha yüksek bulunmuştur; bu durum, dijital oyunların bireylerin günlük yaşamlarını önemli ölçüde etkileyebilecek düzeyde bir bağımlılık oluşturabileceğini göstermektedir.
Dijital oyun bağımlılığı, ortaöğretim dönemindeki öğrencilerin yaşamlarını yalnızca akademik başarı veya sosyal çevre açısından değil, aynı zamanda fiziksel aktivite alışkanlıkları ve spora olan tutumları üzerinden de etkilemektedir (Alagoz & Keskinkilic, 2022; Bora & Karuç, 2025; Gülü vd., 2023). Dijital oyunlara yönelme ya da dijital oyun bağımlılığı durumu, sadece bireylerin oyun oynama alışkanlıklarıyla değil, aynı zamanda motivasyon düzeyleriyle de şekillenmektedir (Hazar, 2019). Öz Belirleme Kuramı çerçevesinde içsel ve dışsal motivasyon boyutları, bireylerin davranışlarını açıklamada önemli bir referans olabilir (Deci & Ryan, 1985). Öz Belirleme teorisi, özerklik, yeterlilik ve ilişkiselliğe odaklanır. Ryan ve Deci'nin (2020) belirttiği gibi, özellikle içsel motivasyonun sürdürülebilir olması, bireylerin bu üç temel ihtiyacının karşılanmasına bağlıdır. Nitekim Ryan ve Deci (2020), içsel motivasyonun çevresel koşullar tarafından belirlenebileceğini ve ihtiyaçların tatmin edilmediği durumlarda bireylerin dışsal ya da kontrol odaklı motivasyonlara yönelebileceğini

vurgulamıştır. Bireylerin dışsal motivasyona yönelmesi; ödül, puan, statü ya da övgü gibi nedenlerle gerçekleşmektedir (Deci & Ryan, 1985; Ryan & Deci, 2020). Nitekim dışsal motivasyonun çevresel etkenlerle şekillenerek, bireyin davranışlarını anlamlı biçimde etkilediği farklı gruplar üzerinde de kanıtlanmıştır (Ateş vd., 2024). Spora katılım motivasyonu açısından değerlendirildiğinde, öğrencilerin spora yönelme nedenleri içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk boyutları üzerinden açıklanabilir (Namlı & Tekkurşun Demir, 2024). İçsel motivasyon bireyin motive olma durumunu nasıl sağladığını ifade ederken, dışsal motivasyon ise bireyi hangi unsurlar ile motive olduğu ile ilgilenmektedir (Ulukuş, 2019). Örneğin, öğrencinin spora keyif almak ve kendini geliştirmek için katılması içsel motivasyonla; takdir görmek, başarılı görünmek ya da beğeni almak için katılması ise dışsal motivasyonla açıklanabilir. Literatürde oyun bağımlılığına ilişkin çalışmaların çoğunlukla psikolojik, sosyal ve akademik sonuçlara odaklandığı görülmektedir (Ghali vd., 2023; Kristensen vd., 2021; Limone vd., 2023).

Buna karşın, bu araştırmanın amacı, lise öğrencilerinde oyun bağımlılığı ile spora katılım motivasyonu arasındaki ilişkiyi incelemek ve oyun bağımlılığı, içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk düzeylerinin cinsiyet, yaş, sınıf düzeyi ve lisanslı sporcu olma durumuna göre farklılaşıp farklılaşmadığını belirlemektir.

YÖNTEM

Araştırma Modeli

Bu araştırmada, nicel araştırma yöntemlerinden korelasyonel araştırma deseni kullanılmıştır. Korelasyonel araştırma deseni, lise öğrencilerinin oyun bağımlılığı, egzersize katılımdaki içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk düzeyleri arasındaki ilişkilerin incelenmesi amacıyla kullanılmıştır. Korelasyonel araştırmalar, neden-sonuç ilişkisiyle ilgili fikir vermektedir (Fraenkel ve ark., 2012). Ayrıca mevcut çalışmada oyun bağımlılığı ve egzersize katılım motivasyonu düzeylerinin cinsiyet, yaş, sınıf düzeyi ve lisanslı sporcu olma durumuna göre farklılaşıp farklılaşmadığını belirlemek amacıyla karşılaştırmalı analizler yapılmıştır.

Evren ve Örneklem

Araştırma kapsamında veri toplama sürecinde, yaygın olarak tercih edilen kolayda örnekleme yöntemi kullanılmıştır. Bu yöntemde, Erzurum ilinde bulunan ve araştırma izinleri alınan liselerde öğrenim gören, gönüllü olarak katılım göstermeyi kabul eden öğrencilere ulaşılmıştır (Özdemir, 2008). Araştırmanın evrenini Erzurum ilindeki lise öğrencileri oluşturmaktadır. Araştırma verileri Erzurum ilinde yer alan toplam 4 farklı liseden toplanmıştır. Katılımcıların belirlenmesinde yalnızca gönüllülük esas alınmamış, belirli ön koşullar da uygulanmıştır. Bu ön koşul soruları şunlardır: (1) “Son bir ay içerisinde, herhangi bir elektronik cihaz (telefon, tablet, bilgisayar, oyun konsolu vb.) aracılığıyla dijital oyun oynadınız mı?” ve (2) “Dijital oyun oynadığınız zaman, bu etkinlik genellikle günde toplam ne kadar süreyi kapsamaktadır?”. Ön değerlendirme sonucunda, ilk soruya "hayır" cevabı veren ve ikinci soruda "günde 10 dakikadan az" yanıtını veren öğrenciler çalışma dışı bırakılmıştır. Başlangıçta toplam 393 öğrenciye ulaşılmış; ancak bu ön koşulları sağlamayan öğrenciler çıkarıldığında, analizlere dâhil edilen katılımcı sayısı 319 olmuştur. Araştırmaya katılan lise öğrencilerinin %53.6’sı kız, %46.4’ü erkektir. Sınıf düzeyine göre katılımcıların %17.8’i (57 katılımcı) 9. sınıf, %28.5’i (91 katılımcı) 10. sınıf, %37.0’ı (118 katılımcı) 11. sınıf ve %16.6’sı (53 katılımcı) 12. sınıf öğrencisidir. Ayrıca, araştırmaya katılan katılımcıların yaş ortalaması 16.32 olarak bulunmuştur.

Veri Toplama Araçları

Kişisel Bilgi Formu

Araştırmada katılımcıların cinsiyet, yaş, sınıf düzeyi, lisanslı sporcu olma durumu ve dijital oyun oynama durumlarına ilişkin bilgilerini belirlemek amacıyla kişisel bilgi formu kullanılmıştır.

Egzersize Katılım Motivasyonu Ölçeği

Bu araştırmada kullanılan Egzersize Katılım Motivasyonu Ölçeği (EKMÖ), Namlı ve Tekkurşun Demir (2024) tarafından geliştirilmiş, geçerlilik ve güvenilirlik çalışmaları yapılmış bir ölçme aracıdır. Ölçek, bireylerin egzersize katılım motivasyonlarını ölçmeyi hedeflemekte ve içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk olmak üzere üç alt boyuttan oluşmaktadır. Hazırlanan ölçek, 21 madde ve 5’li Likert tipi bir derecelendirme ölçeği ile uygulanmaktadır.

Oyun Bağımlılığı Ölçeği

Bu araştırmada Oyun Bağımlılığı Ölçeği (OBÖ) kullanılmıştır. Ölçek, Lemmens, Valkenburg ve Peter (2009) tarafından geliştirilmiş, Akın vd. (2016) tarafından Türkçe'ye uyarlanmış geçerli ve güvenilir bir ölçme aracıdır. Ölçek, ergenlerin oyun bağımlılığı düzeylerini ölçmek amacıyla geliştirilen 7 maddelik, tek boyutlu bir ölçektir. Beşli Likert tipi bir derecelendirme kullanılmaktadır.

Verilerin Analizi

Mevcut araştırmada elde edilen veriler, JASP 0.19.3.0 yazılımı aracılığıyla analiz edilmiştir. Verilerin normallik dağılım özelliklerini değerlendirmek amacıyla, çarpıklık ve basıklık değerleri incelenmiştir. Elde edilen değerlerin kabul edilebilir sınırlar içerisinde yer alması, verilerin normal dağılım gösterdiğine işaret etmekte ve normallik varsayımını sağlamaktadır (George & Mallery, 2010). Katılımcıların demografik özelliklerini belirlemek amacıyla frekans ve yüzde değerleri; araştırma değişkenlerinin genel düzeylerini ortaya koymak amacıyla ortalama, standart sapma, çarpıklık ve basıklık değerleri hesaplanmıştır. Araştırma modelinde yer alan değişkenler arasındaki ilişkileri belirlemek üzere Pearson korelasyon analizi uygulanmıştır. Oyun bağımlılığı, içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk puanlarının cinsiyet ve lisanslı sporcu olma durumuna göre farklılaşıp farklılaşmadığını belirlemek amacıyla bağımsız örneklem t-testi kullanılmıştır. Sınıf düzeyi ve yaş değişkenlerine göre farklılıkları incelemek amacıyla tek yönlü varyans analizi (ANOVA) uygulanmıştır. ANOVA sonucunda anlamlı farklılık bulunan değişkenlerde farkın hangi gruplar arasında olduğunu belirlemek amacıyla Tukey post-hoc testi kullanılmıştır.

BULGULAR

Çalışmaya katılan lise öğrencilerinden elde edilen veriler analiz edilerek ilk olarak katılımcıların demografik özellikleri incelenmiştir. Ardından oyun bağımlılığı, içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk değişkenlerine ilişkin tanımlayıcı istatistikler değerlendirilmiştir. Daha sonra değişkenlerin cinsiyet, lisanslı sporcu olma durumu, sınıf düzeyi ve yaşa göre farklılaşıp farklılaşmadığı analiz edilmiş; son olarak değişkenler arasındaki korelasyonel ilişkiler incelenmiştir.

Tablo 1. Katılımcıların demografik özellikleri

Değişken	Grup	n	%
Cinsiyet	Erkek	148	46.40
	Kız	171	53.60
Sınıf	9. sınıf	57	17.87
	10. sınıf	91	28.53
	11. sınıf	118	36.99
	12. sınıf	53	16.61
Yaş	15	88	27.59
	16	99	31.03
	17	75	23.51
	18	57	17.87
Lisanslı sporcu olma durumu	Evet	88	27.59
	Hayır	231	72.41

Tablo 1 incelendiğinde, araştırmaya toplam 319 lise öğrencisinin katıldığı görülmektedir. Katılımcıların 148'i erkek (%46.40), 171'i kızdır (%53.60). Sınıf düzeyine göre öğrencilerin 57'si 9. sınıf (%17.87), 91'i 10. sınıf (%28.53), 118'i 11. sınıf (%36.99) ve 53'ü 12. Sınıf (%16.61) düzeyindedir. Yaş dağılımı incelendiğinde katılımcıların 88'inin 15 yaş (%27.59), 99'unun 16 yaş (%31.03), 75'inin 17 yaş

(%23.51) ve 57'sinin 18 yaş (%17.87) grubunda yer aldığı belirlenmiştir. Ayrıca katılımcıların 88'i (%27.59) lisanslı sporcu olduğunu, 231'i (%72.41) ise lisanslı sporcu olmadığını belirtmiştir.

Tablo 2. Değişkenlere ilişkin tanımlayıcı istatistikler

Değişken	n	Ortalama	SS	Çarpıklık	Basıklık
Oyun Bağımlılığı	319	2.48	1.07	0.59	1.04
İçsel Motivasyon	319	3.29	0.86	-0.16	-0.05
Dışsal Motivasyon	319	3.07	0.97	-0.16	-0.51
Motivasyonsuzluk	319	3.08	0.99	-0.02	-0.45

Tablo 2'ye göre, öğrencilerin oyun bağımlılığı puan ortalaması 2.48±1.07 olarak belirlenmiştir. Egzersize katılım motivasyonu boyutları incelendiğinde içsel motivasyon puan ortalamasının 3.29±0.86, dışsal motivasyon puan ortalamasının 3.07±0.97 ve motivasyonsuzluk puan ortalamasının 3.08±0.99 olduğu görülmektedir. Değişkenlere ait çarpıklık ve basıklık değerlerinin kabul edilebilir sınırlar içerisinde yer alması, verilerin normal dağılıma yakın olduğunu göstermektedir.

Tablo 3. Cinsiyete göre bağımsız örneklem t-testi sonuçları

Değişken	Erkek Ort.±SS	Kız Ort.±SS	t	sd	p	Cohen's d	Anlamlı Fark
Oyun Bağımlılığı	2.74±1.06	2.26±1.02	4.087	317	<.001	0.459	Erkek > Kız
İçsel Motivasyon	3.36±0.83	3.23±0.87	1.318	317	.189	0.148	Yok
Dışsal Motivasyon	3.13±0.96	3.02±0.97	1.023	317	.307	0.115	Yok
Motivasyonsuzluk	3.14±1.01	3.03±0.97	0.976	317	.330	0.110	Yok

Not. Erkek n=148, kız n=171.

Tablo 3 incelendiğinde, cinsiyete göre yalnızca oyun bağımlılığı puanlarında anlamlı farklılık olduğu görülmektedir, t(317)=4.087, p<.001. Erkek öğrencilerin oyun bağımlılığı puan ortalaması kız öğrencilerden daha yüksektir. Cohen's d değeri incelendiğinde bu farkın küçük-orta düzeyde bir etkiye sahip olduğu söylenebilir. İçsel motivasyon, dışsal motivasyon ve motivasyonsuzluk puanlarında ise cinsiyete göre anlamlı farklılık bulunmamıştır.

Tablo 4. Lisanslı sporcu olma durumuna göre bağımsız örneklem t-testi sonuçları

Değişken	Lisanslı Sporcu Ort.±SS	Lisanslı Sporcu Değil Ort.±SS	t	sd	p	Cohen's d	Anlamlı Fark
Oyun Bağımlılığı	2.73±1.01	2.39±1.07	2.571	317	.011	0.322	Lisanslı sporcu > Lisanslı sporcu değil
İçsel Motivasyon	3.43±0.79	3.24±0.88	1.834	317	.068	0.230	Yok
Dışsal Motivasyon	3.16±1.00	3.03±0.95	1.062	317	.289	0.133	Yok
Motivasyonsuzluk	2.98±1.03	3.12±0.97	-1.127	317	.261	-0.141	Yok

Not. Lisanslı sporcu n=88, lisanslı sporcu değil n=231.

Tablo 4'e göre, lisanslı sporcu olma durumuna göre yalnızca oyun bağımlılığı puanlarında anlamlı farklılık bulunmuştur, t(317)=2.571, p=.011. Lisanslı sporcu olan öğrencilerin oyun bağımlılığı puan

ortalaması, lisanslı sporcu olmayan öğrencilerden daha yüksektir. Cohen's d değeri bu farkın küçük düzeyde bir etkiye sahip olduğunu göstermektedir. İçsel motivasyon, dışsal motivasyon ve motivasyonsuzluk puanlarında ise lisanslı sporcu olma durumuna göre anlamlı farklılık saptanmamıştır.

Tablo 5. Sınıf düzeyine göre tek yönlü ANOVA sonuçları

Değişken	F	sd	p	ω²	Anlamlı Post-hoc Farkı
Oyun Bağımlılığı	0.633	3,312	.594	.000	Yok
İçsel Motivasyon	2.231	3,312	.085	.012	Yok
Dışsal Motivasyon	1.357	3,312	.256	.003	Yok
Motivasyonsuzluk	0.274	3,312	.844	.000	Yok

Tablo 5 incelendiğinde, sınıf düzeyine göre oyun bağımlılığı, içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk puanlarında anlamlı farklılık bulunmadığı görülmektedir. Bu bulgu, öğrencilerin sınıf düzeylerinin araştırmada ele alınan değişkenler üzerinde anlamlı bir farklılaşma oluşturmadığını göstermektedir.

Tablo 6. Yaşa göre tek yönlü ANOVA sonuçları

Değişken	F	sd	p	ω²	Anlamlı Post-hoc Farkı
Oyun Bağımlılığı	0.835	3,312	.475	.000	Yok
İçsel Motivasyon	0.097	3,312	.961	.000	Yok
Dışsal Motivasyon	0.444	3,312	.722	.000	Yok
Motivasyonsuzluk	3.307	3,312	.021	.021	17 yaş > 18 yaş

Tablo 6'ya göre, yaş değişkeni açısından oyun bağımlılığı, içsel motivasyon ve dışsal motivasyon puanlarında anlamlı farklılık bulunmamıştır. Buna karşın motivasyonsuzluk puanlarında yaşa göre anlamlı farklılık saptanmıştır, $F(3,312)=3.307$, $p=.021$, $\omega^2=.021$. Tukey post-hoc testi sonucunda bu farklılığın 17 yaş ile 18 yaş grupları arasında olduğu belirlenmiştir. Buna göre 17 yaş grubundaki öğrencilerin motivasyonsuzluk puanları 18 yaş grubundaki öğrencilerden anlamlı düzeyde daha yüksektir. Omega kare değeri, bu farklılığın küçük düzeyde bir etkiye sahip olduğunu göstermektedir.

Tablo 7. Değişkenler arası Pearson korelasyon sonuçları

Değişkenler	Oyun Bağımlılığı	İçsel Motivasyon	Dışsal Motivasyon	Motivasyonsuzluk
1. Oyun Bağımlılığı	—			
2. İçsel Motivasyon	.083	—		
3. Dışsal Motivasyon	.254***	.541***	—	
4. Motivasyonsuzluk	-.263***	-.076	-.187***	—

Not. ***p ≤ .001.

Tablo 7'ye göre, oyun bağımlılığı ile içsel motivasyon arasında pozitif yönde ancak istatistiksel olarak anlamlı olmayan bir ilişki bulunmaktadır. Buna karşın oyun bağımlılığı ile dışsal motivasyon arasında pozitif yönde ve anlamlı bir ilişki saptanmıştır ($r=.254$, $p<.001$). Bu bulgu, oyun bağımlılığı düzeyi arttıkça dışsal motivasyon düzeyinin de arttığını göstermektedir.

Oyun bağımlılığı ile motivasyonsuzluk arasında ise negatif yönde ve anlamlı bir ilişki bulunmuştur (r=-.263, p<.001). Ayrıca içsel motivasyon ile dışsal motivasyon arasında pozitif yönde ve anlamlı bir ilişki vardır (r=.541, p<.001). Dışsal motivasyon ile motivasyonsuzluk arasında ise negatif yönde ve anlamlı bir ilişki saptanmıştır (r=-.187, p<.001). İçsel motivasyon ile motivasyonsuzluk arasındaki ilişki ise istatistiksel olarak anlamlı değildir.

TARTIŞMA

Bu araştırmanın amacı, lise öğrencilerinde oyun bağımlılığı ile spora katılım motivasyonu arasındaki ilişkileri incelemek; ayrıca oyun bağımlılığı ile spora katılım motivasyonunun alt boyutlarının cinsiyet, yaş, sınıf düzeyi ve lisanslı sporcu olma durumuna göre farklılaşıp farklılaşmadığını belirlemektir. Araştırma bulguları, oyun bağımlılığının dışsal motivasyon ile pozitif, motivasyonsuzluk ile ise negatif yönde ilişkili olduğunu göstermiştir. Bunun yanında erkek öğrencilerin ve lisanslı sporcu olan öğrencilerin oyun bağımlılığı düzeylerinin daha yüksek olduğu belirlenirken, spora katılım motivasyonunun büyük ölçüde demografik değişkenlerden etkilenmediği, yalnızca motivasyonsuzluk boyutunun yaş değişkenine göre anlamlı farklılık gösterdiği saptanmıştır.

Araştırmanın temel bulgularından biri, oyun bağımlılığı ile dışsal motivasyon arasında pozitif, motivasyonsuzluk arasında ise negatif yönde anlamlı ilişkilerin bulunmasıdır. Buna karşın oyun bağımlılığı ile içsel motivasyon arasında anlamlı bir ilişki saptanmamıştır. Bu bulgu, dijital oyun bağımlılığı ile motivasyonel süreçler arasında ilişki olduğunu gösteren çalışmalarla paralellik göstermektedir. Hazar (2019), dijital oyun oynama motivasyonu ile dijital oyun bağımlılığı arasında anlamlı ilişkiler bulunduğunu; özellikle başarı, rekabet ve eğlenme gibi motivasyon kaynaklarının oyun bağımlılığıyla ilişkili olduğunu bildirmiştir. Benzer şekilde Limone ve arkadaşları (2023), video oyun bağımlılığının ödül beklentisi, davranışsal pekiştirme ve psikolojik sonuçlarla ilişkili olduğunu vurgulamıştır. Spor ve fiziksel aktivite bağlamındaki çalışmalar da mevcut bulguyu desteklemektedir. Çar ve Ahraz (2022), ortaokul öğrencilerinde dijital oyun bağımlılığı farkındalığı ile fiziksel aktiviteye katılım motivasyonu arasında anlamlı ilişki bulunduğunu rapor etmiştir. Karuç ve arkadaşları (2025), ergenlerde spora katılım motivasyonu, spora yönelik tutum ve dijital oyun bağımlılığı arasında anlamlı ilişkiler olduğunu; spora katılım motivasyonunun dijital oyun bağımlılığıyla ilişkili bir değişken olduğunu belirtmiştir. Ucar ve ark. (2026) ise ergenlerde dijital oyun bağımlılığı ile fiziksel aktiviteye katılım motivasyonu arasındaki ilişkinin anlamlı olduğunu ve erkek öğrencilerin hem dijital oyun bağımlılığı hem de fiziksel aktivite motivasyonu düzeylerinin daha yüksek olduğunu bildirmiştir. Gülü ve arkadaşları (2023) da ergenlerde fiziksel aktivite düzeyi ile dijital oyun bağımlılığı arasındaki ilişkinin önemine dikkat çekmiştir. Mevcut araştırmada ilişkinin özellikle dışsal motivasyon boyutunda ortaya çıkması, dijital oyunların ödül, puan, seviye atlama, rekabet ve başarı hissi gibi dışsal pekiştiricilere dayalı yapısıyla açıklanabilir. Ryan ve Deci'nin (2020) Öz Belirleme Kuramı'na göre dışsal motivasyon, bireyin davranışlarını ödül, takdir, sosyal kabul veya performans beklentisi gibi çevresel faktörler doğrultusunda sürdürmesini ifade etmektedir. Bu bağlamda oyun bağımlılığı eğilimi gösteren öğrencilerin spor ortamında da benzer dışsal kazanımlara daha duyarlı olmaları beklenebilir. Oyun bağımlılığı ile motivasyonsuzluk arasındaki negatif ilişki ise bu öğrencilerin genel anlamda motivasyonsuz olmadıklarını; aksine motivasyonlarının dijital oyunların sunduğu ödül ve başarı temelli deneyimlere yöneldiğini düşündürmektedir. Bu yönüyle mevcut bulgular, oyun bağımlılığının spora katılım motivasyonunu bütünüyle azaltmadığını; daha çok motivasyonun niteliğini, özellikle dışsal motivasyon boyutunu etkileyebileceğini düşündürmektedir.

Araştırmada erkek öğrencilerin oyun bağımlılığı düzeylerinin kız öğrencilere göre anlamlı düzeyde daha yüksek olduğu belirlenmiştir. Bu bulgu, oyun bağımlılığında cinsiyet farklılığını ortaya koyan literatürle örtüşmektedir. Örneğin, Ko ve arkadaşları (2005) erkek ergenlerin çevrim içi oyun bağımlılığı düzeylerinin kızlara göre anlamlı düzeyde daha yüksek olduğunu ve bu farklılığın özellikle oyun oynama motivasyonları ile ilişkili olduğunu bildirmiştir. Benzer şekilde Meng ve arkadaşları (2022) tarafından gerçekleştirilen meta-analizde de dijital oyun bağımlılığı prevalansının erkeklerde daha yüksek olduğu rapor edilmiş ve erkek cinsiyetin önemli bir risk faktörü olduğu belirtilmiştir. Varchetta ve arkadaşları (2024) ise erkeklerin daha çok oyun temelli dijital bağımlılık davranışları sergilerken kadınların sosyal medya temelli dijital kullanım örüntülerine yöneldiğini göstermiştir. Ayrıca Gisbert-Pérez ve arkadaşları (2024) erkek oyuncuların oyun oynama süresi, rekabetçi oyunlara katılımı ve oyun topluluklarıyla etkileşim düzeylerinin kadınlardan daha yüksek olduğunu bildirmiştir.

Bu durum, erkek öğrencilerin dijital oyunlarla daha yoğun etkileşim kurmaları ve rekabet odaklı oyun türlerine daha fazla yönelmelerinin oyun bağımlılığı riskini artırabileceğini düşündürmektedir.

Araştırmada lisanslı sporcuların oyun bağımlılığı düzeylerinin lisanslı olmayan öğrencilerden daha yüksek olduğu belirlenmiştir. Bu durum, fiziksel aktivite ve spor katılımının dijital oyun bağımlılığını azalttığını bildiren önceki araştırmalardan farklılık göstermektedir (Gülü ve ark., 2023; Karuç ve ark., 2025; Ucar ve ark., 2026). Mevcut farklılığın, araştırma grubunun lisanslı sporculardan oluşması, bu öğrencilerin rekabet odaklı özelliklere sahip olmaları ve dijital oyunları boş zaman etkinliği ya da rekabet ihtiyacını karşılayan bir araç olarak daha sık kullanmalarından kaynaklanabileceği düşünülmektedir. Son yıllarda özellikle e-spor ve geleneksel spor arasındaki geçişkenliği inceleyen çalışmalar, rekabet yönelimi yüksek bireylerin dijital oyunlara daha fazla ilgi gösterebildiğini ortaya koymaktadır. Bu nedenle mevcut araştırmada elde edilen bulgunun, spor yapmanın tek başına dijital oyun bağımlılığını azaltmadığını; sporcuların oyun oynama amaçları ve boş zaman alışkanlıkları gibi bireysel özelliklerin de bu ilişkide belirleyici olabileceğini gösterdiği söylenebilir.

Araştırmada sınıf düzeyine göre oyun bağımlılığı, içsel motivasyon, dışsal motivasyon ve motivasyonsuzluk puanlarında anlamlı bir farklılık bulunmamıştır. Bu bulgu, sınıf düzeyinin dijital oyun bağımlılığı üzerinde belirleyici bir değişken olmadığını bildiren önceki araştırmalarla benzerlik göstermektedir. Örneğin Sivrikaya (2023), kaynaştırma öğrencileri üzerinde gerçekleştirdiği çalışmada dijital oyun bağımlılığı düzeylerinin sınıf düzeyine göre anlamlı farklılık göstermediğini bildirmiştir. Benzer şekilde Kaman ve Bulut (2024) da ortaokul öğrencileriyle yürüttükleri araştırmada dijital oyun bağımlılığı puanlarının sınıf düzeyine göre değişmediğini rapor etmiştir. Ayrıca Cırıs (2022) tarafından lise öğrencileri üzerinde gerçekleştirilen araştırmada da dijital oyun bağımlılığı düzeylerinin sınıf düzeyi bakımından anlamlı farklılık göstermediği belirtilmiştir. Mevcut araştırmada yalnızca oyun bağımlılığı değil, spora katılım motivasyonunun alt boyutlarında da sınıf düzeyine göre anlamlı farklılık bulunmaması, lise öğrenimi sürecinde öğrencilerin dijital oyun kullanım alışkanlıkları ile spora katılım motivasyonlarının sınıf ilerledikçe belirgin biçimde değişmediğini düşündürmektedir.

Araştırmada yalnızca motivasyonsuzluk puanlarının yaşa göre farklılaştığı, 17 yaş grubunun motivasyonsuzluk düzeyinin 18 yaş grubundan daha yüksek olduğu belirlenmiştir. Buna karşın oyun bağımlılığı ile içsel ve dışsal motivasyon puanlarında yaşa göre anlamlı farklılık bulunmamıştır. Bu sonuç, yaşın tek başına motivasyonel süreçleri açıklamada yeterli olmadığını bildiren çalışmalarla uyumludur. Ryan ve Deci'ye (2020) göre motivasyonun niteliği kronolojik yaştan çok bireyin özerklik, yeterlik ve ilişkisellik gibi temel psikolojik ihtiyaçlarının karşılanma düzeyinden etkilenmektedir. Benzer şekilde Kaya ve arkadaşları (2023), ergenlerde çevrim içi oyun bağımlılığını yaş değişkeninden ziyade temel psikolojik ihtiyaçların karşılanma düzeyinin açıkladığını göstermiştir. Bu nedenle mevcut araştırmada 17 ve 18 yaş grupları arasında yalnızca motivasyonsuzluk boyutunda farklılık bulunması, yaşın doğrudan belirleyici olmasından ziyade bu dönemde yaşanan gelişimsel ve psikolojik değişimlerle ilişkili olabilir.

SONUÇ

Bu araştırmada lise öğrencilerinde oyun bağımlılığı ile spora katılım motivasyonu arasındaki ilişkiler incelenmiş, ayrıca oyun bağımlılığı ile spora katılım motivasyonunun alt boyutlarının cinsiyet, yaş, sınıf düzeyi ve lisanslı sporcu olma durumuna göre farklılaşıp farklılaşmadığı değerlendirilmiştir. Araştırma sonucunda oyun bağımlılığı ile dışsal motivasyon arasında pozitif, motivasyonsuzluk arasında ise negatif yönde anlamlı ilişkiler olduğu belirlenirken, içsel motivasyon ile oyun bağımlılığı arasında anlamlı bir ilişki bulunmamıştır. Demografik değişkenler açısından erkek öğrencilerin ve lisanslı sporcu olan öğrencilerin oyun bağımlılığı düzeylerinin daha yüksek olduğu, buna karşın spora katılım motivasyonunun alt boyutlarının büyük ölçüde demografik değişkenlerden etkilenmediği belirlenmiştir. Ayrıca sınıf düzeyine göre oyun bağımlılığı ve spora katılım motivasyonunda anlamlı bir farklılık bulunmazken, yaş değişkeninde yalnızca motivasyonsuzluk boyutunun farklılaştığı ve 17 yaş grubunun motivasyonsuzluk düzeyinin 18 yaş grubundan daha yüksek olduğu tespit edilmiştir. Bu bulgular doğrultusunda dijital oyun bağımlılığının öğrencilerin spora katılım motivasyonunu tamamen azaltmadığı, ancak motivasyonun niteliğiyle ilişkili olabileceği söylenebilir. Özellikle dışsal motivasyon ile belirlenen ilişki, dijital oyunların ödül ve rekabet temelli yapısının öğrencilerin spora katılım süreçlerine de yansıyabileceğini göstermektedir.

Araştırmanın Etik ve İzin Süreci

Bu çalışmada kullanılan verilerin toplanabilmesi için gerekli etik kurul onayı ve araştırma uygulama izni alınmıştır. Araştırmanın etik açıdan uygunluğu, Erzurum Teknik Üniversitesi Bilimsel Araştırma ve Yayın Etik Kurulunun 19.06.2025 tarihli, 09 toplantı sayılı ve 19 karar sayılı kararı ile onaylanmıştır. Araştırmanın Millî Eğitim Bakanlığına bağlı eğitim kurumlarında uygulanabilmesi için ayrıca gerekli araştırma uygulama izni alınmıştır. Çalışma, 09.07.2025 tarihli ve MEB.TT.2025.028252.01 sayılı izin kapsamında Millî Eğitim Bakanlığı tarafından onaylanmıştır.

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SPORCULARDA EYSENCK KİŞİLİK ÖZELLİKLERİ İLE PSİKOLOJİK PERFORMANS BİLEŞENLERİ ARASINDAKİ İLİŞKİLERİN VE DEMOGRAFİK DEĞİŞKENLERE GÖRE FARKLILIKLARININ İNCELENMESİ

EXAMINATION OF THE RELATIONSHIPS BETWEEN EYSENCK PERSONALITY TRAITS AND PSYCHOLOGICAL PERFORMANCE COMPONENTS IN ATHLETES AND THEIR DIFFERENCES ACCORDING TO DEMOGRAPHIC VARIABLES

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ÖZET

Sportif performansın sürdürülebilirliği, fiziksel ve teknik yeterliliklerin yanı sıra sporcuların kişilik özellikleri ve psikolojik performans bileşenleriyle de yakından ilişkilidir. Bu araştırmada sporcuların Eysenck kişilik özellikleri ile bedensel ve bilişsel kaygı, güdülenme ve kendine güven düzeyleri arasındaki ilişkilerin incelenmesi ve söz konusu değişkenlerin cinsiyet, spor branşı ve sporculuk düzeyine göre farklılaşıp farklılaşmadığının belirlenmesi amaçlanmıştır. Korelasyonel araştırma deseninde yürütülen çalışmaya Erzurum'da aktif olarak spor yapan 230 sporcu katılmıştır. Katılımcıların 134'ü erkek, 96'sı kadın; 112'si bireysel, 118'i takım sporcusu; 179'u amatör ve 51'i millî sporcudur. Veriler Kişisel Bilgi Formu, Eysenck Kişilik Anketi-Gözden Geçirilmiş Kısaltılmış Formu ve Sporda Psikolojik Performans Değerlendirme Ölçeği ile toplanmış; bağımsız örneklemler t-testi ve Pearson korelasyon analizi kullanılarak çözümlenmiş, anlamlılık düzeyi $p<.05$ olarak kabul edilmiştir. Bulgular, kadın sporcuların sosyal istenirlik ve toplam kişilik puanlarının, erkek sporcuların ise kendine güven düzeylerinin daha yüksek olduğunu göstermiştir. Takım sporcularının nörotisizm puanları daha yüksek bulunurken bireysel sporcuların psikotisizm ile bedensel ve bilişsel kaygı puanlarının daha yüksek olduğu belirlenmiştir. Millî sporcuların psikotisizm düzeyleri amatör sporculardan daha yüksektir. Dışadönüklük kaygı ile negatif, güdülenme ve kendine güven ile pozitif; nörotisizm kaygı ile pozitif, kendine güven ile negatif ilişkili bulunmuştur. Ayrıca güdülenme ile kendine güven arasında güçlü ve pozitif ilişki saptanmıştır. Sonuç olarak kişilik özelliklerinin sporcuların psikolojik performansında önemli bir rol oynadığı görülmüştür. Sporculara yönelik psikolojik beceri eğitimlerinin kişilik özelliklerine göre bireyselleştirilmesi ve kaygı yönetimi, güdülenme ve kendine güven çalışmalarına ağırlık verilmesi önerilmektedir.

Anahtar kelimeler: Eysenck kişilik özellikleri, Psikolojik performans, Sporcular, Güdülenme, Kendine güven.

ABSTRACT

The sustainability of athletic performance is closely associated not only with physical and technical competencies but also with athletes' personality traits and psychological performance components. This study aimed to examine the relationships between athletes' Eysenck personality traits and their levels of somatic and cognitive anxiety, motivation, and self-confidence, and to determine whether these variables differed according to gender, type of sport, and athletic level. Conducted using a correlational

research design, the study included 230 athletes who were actively engaged in sports in Erzurum. Of the participants, 134 were male and 96 were female; 112 participated in individual sports and 118 in team sports; 179 were amateur athletes and 51 were national-level athletes. Data were collected using a Personal Information Form, the Eysenck Personality Questionnaire-Revised Short Form, and the Psychological Performance Assessment Scale in Sports. The data were analyzed using the independent-samples t-test and Pearson correlation analysis, with the level of significance set at $p<.05$. The findings showed that female athletes had higher social desirability and total personality scores, whereas male athletes had higher levels of self-confidence. Team-sport athletes had higher neuroticism scores, while individual-sport athletes had higher psychoticism as well as somatic and cognitive anxiety scores. National-level athletes had higher psychoticism levels than amateur athletes. Extraversion was negatively associated with anxiety and positively associated with motivation and self-confidence, whereas neuroticism was positively associated with anxiety and negatively associated with self-confidence. In addition, a strong and positive relationship was found between motivation and self-confidence. In conclusion, personality traits were found to play an important role in athletes' psychological performance. It is recommended that psychological skills training for athletes be individualized according to personality traits, with particular emphasis on anxiety management, motivation, and self-confidence interventions.
Keywords: Eysenck personality traits, Psychological performance, Athletes, Motivation, Self-confidence.

GİRİŞ

Spor performansı yalnızca fiziksel kapasite, teknik beceri ve taktiksel yeterlilik ile açıklanamamakta; psikolojik özellikler de performansın önemli belirleyicileri arasında yer almaktadır. Özellikle rekabet ortamlarında sporcuların karşılaştıkları baskı, stres ve beklentileri etkili biçimde yönetebilmeleri, başarılı performansın sürdürülebilmesi açısından kritik öneme sahiptir (Birrer & Morgan, 2010; Gucciardi vd., 2015). Bu nedenle son yıllarda spor psikolojisi alanında yapılan araştırmalar, performansı etkileyen psikolojik faktörlerin belirlenmesine ve geliştirilmesine odaklanmaktadır (Weinberg & Gould, 2019). Psikolojik performans, sporcunun antrenman ve müsabaka süreçlerinde zihinsel becerilerini etkili biçimde kullanabilme kapasitesi olarak tanımlanmaktadır. Bu yapı; performans sırasında ortaya çıkan bedensel ve bilişsel kaygının yönetilmesi, hedefe yönelik güdülenmenin sürdürülmesi ve kendine güvenin korunması gibi performansı doğrudan etkileyen psikolojik bileşenleri kapsamaktadır (Aydoğan & Konaş, 2022). Spor psikolojisi alanında yapılan araştırmalar, psikolojik performans düzeyi yüksek sporcuların stresli durumlarla daha etkili başa çıktıklarını, performanslarını daha istikrarlı biçimde sürdürebildiklerini ve başarı olasılıklarının arttığını göstermektedir (Birrer & Morgan, 2010; Weinberg & Gould, 2019). Buna karşılık yüksek düzeyde bedensel ve bilişsel kaygının performansı olumsuz etkileyebildiği, buna karşın yüksek güdülenme ve kendine güven düzeylerinin sportif başarıyı destekleyen temel psikolojik özellikler arasında yer aldığı bildirilmektedir (Craft vd., 2003; Vealey & Chase, 2008). Bu nedenle psikolojik performansı etkileyen bireysel özelliklerin belirlenmesi, sporcuların performanslarının geliştirilmesine yönelik psikolojik müdahalelerin planlanması açısından önem taşımaktadır.

Kişilik, bireyin düşünce, duygu ve davranış örüntülerini belirleyen, zaman içerisinde görece kararlılık gösteren psikolojik özellikler bütünü olarak tanımlanmaktadır. Spor psikolojisi alanında kişilik özelliklerinin performans üzerindeki etkisini açıklamak amacıyla en yaygın kullanılan yaklaşımlardan biri Eysenck'in biyolojik temelli kişilik kuramıdır. Bu kurama göre kişilik; dışadönüklük, nörotisizm ve psikotisizm olmak üzere üç temel boyuttan oluşmaktadır. Dışadönüklük bireyin sosyal, girişken ve enerjik olmasını; nörotisizm duygusal dengesizlik ve kaygıya yatkınlığı, psikotisizm ise saldırganlık, dürtüsellik ve kişilerarası uyum güçlüğü gibi özellikleri ifade etmektedir (Eysenck & Eysenck, 1985; Karancı vd., 2007). Son yıllarda yapılan araştırmalar, bu kişilik boyutlarının sporcuların psikolojik süreçlerini ve performanslarını farklı düzeylerde etkileyebildiğini göstermektedir (Laborde vd., 2016).

Literatürde özellikle dışadönüklük ve nörotisizm boyutlarının sportif performansla daha güçlü ilişki gösterdiği bildirilmektedir. Dışadönük sporcuların stresli yarışma ortamlarına daha kolay uyum sağladıkları, daha yüksek motivasyon ve kendine güven düzeyine sahip oldukları belirtilmektedir (Laborde vd., 2016; Piepiora, 2021). Buna karşılık nörotisizm düzeyi yüksek sporcuların bilişsel ve bedensel yarışma kaygısını daha yoğun yaşayabildikleri ve kendine güven düzeylerinin daha düşük olabildiği bildirilmektedir (Amaro & Brandão, 2023; Herinasari vd., 2025). Ayrıca kişilik özelliklerinin

sportif performans üzerindeki etkisinde rekabet kaygısının aracı bir rol üstlenebildiği belirtilmektedir (Dai vd., 2026).

Psikotisizm boyutuna ilişkin spor araştırmaları, dışadönüklük ve nörotisizm boyutlarına kıyasla daha sınırlıdır. Dövüş sporcuları üzerinde gerçekleştirilen bir araştırmada psikotisizm ile psikolojik dayanıklılık arasında negatif yönlü bir ilişki bulunduğu raporlanmıştır (da Gama vd., 2018). Ayrıca kişilik özelliklerinin spor branşı, rekabet düzeyi ve performans gereksinimlerine bağlı olarak farklılaşabileceği, özellikle bireysel ve takım sporcuları arasında kişilik profillerinin değişebileceği belirtilmektedir (Laborde vd., 2016). Bununla birlikte Eysenck kişilik özelliklerinin psikolojik performansın temel bileşenleri olan bedensel ve bilişsel kaygı, güdülenme ve kendine güven ile ilişkisini birlikte inceleyen çalışmaların sınırlı olduğu görülmektedir. Bu durum, söz konusu değişkenlerin bir arada değerlendirilmesini gerekli kılmaktadır.

Literatürde kişilik özellikleri ile sportif performans arasındaki ilişkiyi inceleyen çok sayıda araştırma bulunmasına rağmen, bu çalışmaların büyük bölümünde performans fiziksel başarı, yarışma sonucu veya rekabet kaygısı gibi sınırlı değişkenler üzerinden değerlendirilmiştir (Allen vd., 2013; Laborde vd., 2016). Buna karşılık psikolojik performansın temel bileşenleri olan bedensel ve bilişsel kaygı, güdülenme ve kendine güven ile Eysenck kişilik özellikleri arasındaki ilişkileri aynı araştırma kapsamında ele alan çalışmaların oldukça sınırlı olduğu görülmektedir. Ayrıca mevcut araştırmalarda cinsiyet, spor branşı ve sporculuk düzeyinin bu değişkenler üzerindeki etkilerine ilişkin bulguların da tutarsız olduğu dikkat çekmektedir (Kemarat vd., 2022; Piepiora, 2021). Bu nedenle kişilik özellikleri ile psikolojik performans bileşenlerinin birlikte incelenmesi, sporcuların performansını etkileyen psikolojik mekanizmaların daha iyi anlaşılmasına katkı sağlayacaktır.

Bu araştırmanın amacı, sporcularda Eysenck kişilik özellikleri ile psikolojik performans bileşenleri arasındaki ilişkilerin incelenmesi ve bu değişkenlerin cinsiyet, spor branşı ve sporculuk düzeyine göre farklılaşıp farklılaşmadığının belirlenmesidir. Bu doğrultuda araştırmadan elde edilecek bulguların, sporcuların psikolojik performanslarının geliştirilmesine yönelik uygulamalara katkı sağlaması ve spor psikolojisi alanındaki mevcut literatüre yeni kanıtlar sunması beklenmektedir.

YÖNTEM

Araştırma Modeli

Bu araştırmada nicel araştırma yöntemlerinden korelasyonel araştırma deseni kullanılmıştır. Korelasyonel araştırmalar, değişkenler arasındaki ilişkilerin yönü ve düzeyi hakkında bilgi vermektedir (Fraenkel vd., 2012). Araştırmada sporcuların kişilik özellikleri ile bedensel ve bilişsel kaygı, güdülenme ve kendine güven düzeyleri arasındaki ilişkilerin incelenmesi amaçlanmıştır. Ayrıca bu değişkenlerin cinsiyet, spor branşı ve sporculuk durumuna göre farklılaşıp farklılaşmadığı karşılaştırmalı analizlerle değerlendirilmiştir.

Evren ve Örneklem

Araştırmanın örnekleminin belirlenmesinde olasılıklı olmayan örnekleme yöntemlerinden kolayda örnekleme yöntemi tercih edilmiştir (Özdemir, 2008). Bu kapsamda araştırmaya ulaşılabilen, aktif olarak spor yapan ve çalışmaya gönüllü olarak katılmayı kabul eden sporcular dâhil edilmiştir. Araştırmanın evrenini Erzurum İlinde aktif olarak spor yapan sporcular oluştururken, örneklemini araştırmaya katılım ölçütlerini sağlayan toplam 230 sporcu meydana getirmektedir. Çalışmaya katılan sporcuların araştırmaya dâhil edilebilmesi için aktif olarak spor yapıyor olmaları, araştırmaya gönüllü katılım sağlamaları ve veri toplama araçlarını eksiksiz doldurmaları temel ölçütler olarak belirlenmiştir. Bu ölçütleri karşılamayan veya ölçek formlarını eksik dolduran katılımcıların verileri değerlendirme kapsamına alınmamıştır. Araştırmaya katılan sporcuların 134'ü (%58,3) erkek, 96'sı (%41,7) kadındır. Spor branşı bakımından katılımcıların 112'si (%48,7) bireysel sporlarla, 118'i (%51,3) takım sporlarıyla uğraşmaktadır. Sporculuk düzeyi açısından ise katılımcıların 179'u (%77,8) amatör, 51'i (%22,2) milli sporcudur. Katılımcıların yaş ortalaması 21,29±4,06 yıl, spor yapma sürelerinin ortalaması ise 8,19±4,33 yıl olarak belirlenmiştir.

Veri Toplama Araçları

Kişisel Bilgi Formu

Araştırmada katılımcıların demografik özelliklerini belirlemek amacıyla araştırmacı tarafından hazırlanan Kişisel Bilgi Formu kullanılmıştır. Formda katılımcıların cinsiyeti, yaşı, spor branşı

(bireysel/takım), sporculuk durumu (amatör/milli) ve spor yaşına (kaç yıldır spor yaptığı) ilişkin bilgileri belirlemeye yönelik sorular yer almaktadır.

Eysenck Kişilik Anketi-Gözden Geçirilmiş Kısaltılmış Formu (EKA-GGK)

Araştırmada sporcuların kişilik özelliklerini belirlemek amacıyla Francis vd. (1992) tarafından geliştirilen, Türkçe uyarlaması Karancı vd. (2007) tarafından yapılan Eysenck Kişilik Anketi-Gözden Geçirilmiş Kısaltılmış Formu (EKA-GGK) kullanılmıştır. Ölçek toplam 24 maddeden oluşmakta olup dışadönüklük, nörotisizm, psikotisizm ve yalan (sosyal istenirlik) olmak üzere dört alt boyuttan meydana gelmektedir. Maddeler "Evet" ve "Hayır" şeklinde ikili derecelendirme ile yanıtlanmaktadır. Her bir alt boyut 6 maddeden oluşmakta olup alt boyutlardan alınabilecek puanlar 0 ile 6 arasında değişmektedir. Ölçekten elde edilen yüksek puanlar ilgili kişilik özelliğinin daha belirgin olduğunu göstermektedir.

Sporda Psikolojik Performans Değerlendirme Ölçeği (SPPDÖ)

Araştırmada sporcuların psikolojik performans düzeylerini belirlemek amacıyla Sporda Psikolojik Performans Değerlendirme Ölçeği (SPPDÖ) kullanılmıştır. Ölçek, sporcuların psikolojik performanslarını değerlendirmeye yönelik geliştirilmiş olup üç alt boyuttan oluşmaktadır. Bu alt boyutlar; Bedensel ve Bilişsel Kaygı, Güdülenme ve Kendine Güvendir. Ölçek toplam 32 maddeden oluşmakta olup 5'li Likert tipinde derecelendirilmektedir. Katılımcılar her maddeyi 1=Kesinlikle Katılmıyorum ile 5=Kesinlikle Katılıyorum arasında puanlamaktadır. Bedensel ve Bilişsel Kaygı alt boyutu 17 maddeden, Güdülenme alt boyutu 8 maddeden ve Kendine Güven alt boyutu ise 7 maddeden oluşmaktadır. Ölçekten elde edilen yüksek puanlar, ilgili psikolojik performans boyutunun daha yüksek düzeyde olduğunu göstermektedir.

Verilerin Analizi

Araştırma kapsamında elde edilen veriler JASP 0.19.3.0 istatistik paket programı kullanılarak analiz edilmiştir. Analizlere başlamadan önce veri setinin normal dağılım gösterip göstermediği çarpıklık (skewness) ve basıklık (kurtosis) değerleri incelenerek değerlendirilmiştir. Elde edilen çarpıklık ve basıklık katsayılarının kabul edilebilir sınırlar içerisinde yer alması nedeniyle verilerin normal dağılım gösterdiği kabul edilmiş ve parametrik analiz teknikleri tercih edilmiştir (George ve Mallery, 2010). Araştırmaya katılan sporcuların demografik özelliklerini belirlemek amacıyla frekans (f), yüzde (%), aritmetik ortalama ($\bar{X}$), standart sapma (SS), minimum ve maksimum değerler hesaplanmıştır. Araştırmada kullanılan Eysenck Kişilik Ölçeği alt boyutları ile Sporda Psikolojik Performans Envanteri alt boyutlarına ilişkin tanımlayıcı istatistikler de hesaplanmıştır. Katılımcıların cinsiyet, spor branşı (bireysel/takım) ve sporculuk durumu (amatör/milli) değişkenlerine göre Eysenck kişilik özellikleri ile psikolojik performans bileşenlerinin farklılaşıp farklılaşmadığını belirlemek amacıyla Bağımsız Örneklemler t-Testi uygulanmıştır. Gruplar arasındaki farklılıkların etki büyüklüğünü değerlendirmek amacıyla Cohen'in d katsayısı hesaplanmıştır (Cohen, 1988). Araştırmada Eysenck kişilik özellikleri ile sporda psikolojik performans bileşenleri arasındaki ilişkilerin belirlenmesi amacıyla Pearson Korelasyon Analizi uygulanmıştır. Tüm istatistiksel analizlerde anlamlılık düzeyi $p < 0,05$ olarak kabul edilmiştir.

BULGULAR

Araştırmaya katılan sporculardan elde edilen veriler analiz edilerek öncelikle katılımcıların demografik özellikleri ile araştırma değişkenlerine ilişkin tanımlayıcı istatistikler incelenmiştir. Bu kapsamda katılımcıların cinsiyet, yaş, spor branşı, sporculuk durumu ve spor yaşı değişkenlerine ait frekans, yüzde, ortalama ve standart sapma değerleri sunulmuştur. Daha sonra Eysenck kişilik özellikleri (dışadönüklük, nörotisizm, psikotisizm, yalan/sosyal istenirlik ve toplam kişilik puanı) ile sporda psikolojik performans bileşenleri (bedensel ve bilişsel kaygı, güdülenme ve kendine güven) arasındaki farklılıklar cinsiyet, spor branşı ve sporculuk durumuna göre bağımsız örneklemler t-testi ile incelenmiştir. Son olarak Eysenck kişilik özellikleri ile psikolojik performans bileşenleri arasındaki ilişkiler Pearson korelasyon analizi kullanılarak değerlendirilmiştir.

Tablo 1. Katılımcıların Demografik Özellikleri

Değişken	Grup	n	%
Cinsiyet	Erkek	134	58,26
	Kadın	96	41,74
Spor Branşı	Bireysel Spor	112	48,70
	Takım Sporu	118	51,30
Sporculuk Durumu	Amatör Sporcu	179	77,83
	Millî Sporcu	51	22,17

Tablo 1 incelendiğinde, araştırmaya toplam 230 sporcunun katıldığı görülmektedir. Katılımcıların 134'ü erkek (%58.26), 96'sı kadındır (%41.74). Spor branşına göre katılımcıların 112'si bireysel sporlarla (%48.70), 118'i ise takım sporlarıyla (%51.30) ilgilenmektedir. Sporculuk durumu açısından katılımcıların 179'u amatör (%77.83), 51'i millî sporcudur (%22.17). Katılımcıların yaş ortalaması 21.29±4.06 yıl olup yaşları 17 ile 45 arasında değişmektedir. Spor yaşı ortalaması ise 8.19±4.33 yıl olarak belirlenmiş ve spor yaşı değerlerinin 0 ile 22 yıl arasında değiştiği görülmüştür.

Tablo 2. Değişkenlere İlişkin Tanımlayıcı İstatistikler

Değişken	*n*	*M*	*SS*	Çarpıklık	Basıklık
Dışadönüklük	230	0.567	0.281	−0.449	−0.830
Yalan/Sosyal İstenirlik	230	0.646	0.273	−0.596	−0.450
Nörotisizm	230	0.605	0.287	−0.338	−0.875
Psikotisizm	230	0.322	0.208	0.411	−0.104
Eysenck Kişilik Toplam Puanı	230	0.559	0.122	−0.428	0.415
Bedensel ve Bilişsel Kaygı	230	2.835	0.728	0.052	0.556
Güdülenme	230	3.784	0.808	−0.673	0.412
Kendine Güven	230	3.420	0.742	−0.232	0.779

Not. M = ortalama; *SS* = standart sapma.

Tablo 2 incelendiğinde, Eysenck kişilik özelliklerinden dışadönüklük puan ortalamasının 0.567±0.281, yalan/sosyal istenirlik puan ortalamasının 0.646±0.273, nörotisizm puan ortalamasının 0.605±0.287 ve psikotisizm puan ortalamasının 0.322±0.208 olduğu görülmektedir. Katılımcıların Eysenck kişilik toplam puan ortalaması ise 0.559±0.122 olarak belirlenmiştir. Psikolojik performans bileşenleri incelendiğinde, bedensel ve bilişsel kaygı puan ortalamasının 2.835±0.728, güdülenme puan ortalamasının 3.784±0.808 ve kendine güven puan ortalamasının 3.420±0.742 olduğu görülmektedir. Psikolojik performans bileşenleri arasında en yüksek puan ortalaması güdülenme boyutunda, en düşük puan ortalaması ise bedensel ve bilişsel kaygı boyutunda elde edilmiştir. Araştırma değişkenlerine ait çarpıklık değerlerinin -0.673 ile 0.411, basıklık değerlerinin ise -0.875 ile 0.779 arasında değiştiği belirlenmiştir. Çarpıklık ve basıklık değerlerinin kabul edilebilir sınırlar içerisinde bulunması, araştırma değişkenlerine ait puanların normal dağılıma yakın bir dağılım gösterdiğine işaret etmektedir.

Tablo 3. Cinsiyete göre bağımsız örneklem t-testi sonuçları

Değişken	Erkek Ort.±SS	Kız Ort.±SS	t	sd	p	Cohen's d	Anlamlı Fark
Dışadönüklük	0.552±0.293	0.587±0.265	-0.918	228	.360	-0.123	Yok
Yalan/Sosyal İstenirlik	0.607±0.281	0.701±0.254	-2.619	228	.009	-0.350	Kadın > Erkek
Nörotisizm	0.586±0.306	0.632±0.256	-1.204	228	.230	-0.161	Yok
Psikotisizm	0.336±0.212	0.304±0.201	1.152	228	.250	0.154	Yok
Eysenck Kişilik Toplam Puanı	0.542±0.130	0.583±0.105	-2.562	228	.011	-0.343	Kadın > Erkek
Bedensel ve Bilişsel Kaygı	2.773±0.721	2.923±0.733	-1.547	228	.123	-0.207	Yok
Güdülenme	3.794±0.771	3.771±0.860	0.213	228	.832	0.028	Yok
Kendine Güven	3.517±0.713	3.286±0.764	2.355	228	.019	0.315	Erkek > Kadın

Not: Erkek n=134, kadın n=96.

Tablo 3 incelendiğinde, cinsiyete göre yalan/sosyal istenirlik, Eysenck kişilik toplam puanı ve kendine güven değişkenlerinde anlamlı farklılıklar olduğu görülmektedir. Yalan/sosyal istenirlik puanları kadınlarda erkeklere göre anlamlı düzeyde daha yüksektir, t(228)=-2.619, p=.009. Benzer şekilde Eysenck kişilik toplam puanı da kadınlarda erkeklere göre daha yüksek bulunmuştur, t(228)=-2.562, p=.011. Buna karşın kendine güven puanlarının erkeklerde kadınlara göre anlamlı düzeyde daha yüksek olduğu belirlenmiştir, t(228)=2.355, p=.019. Dışadönüklük, nörotisizm, psikotisizm, bedensel ve bilişsel kaygı ile güdülenme değişkenlerinde ise cinsiyete göre anlamlı bir farklılık saptanmamıştır (p>.05). Cohen's d değerleri incelendiğinde, anlamlı farklılıkların küçük düzeyde etki büyüklüğüne sahip olduğu görülmektedir.

Tablo 4. Spor branşına göre bağımsız örneklem t-testi sonuçları

Değişken	Bireysel Ort.±SS	Takım Ort.±SS	t	sd	p	Cohen's d	Anlamlı Fark
Dışadönüklük	0.534±0.267	0.597±0.293	-1.710	228	.089	-0.226	Yok
Yalan/Sosyal İstenirlik	0.638±0.268	0.654±0.278	-0.431	228	.667	-0.057	Yok
Nörotisizm	0.557±0.284	0.651±0.282	-2.530	228	.012	-0.334	Takım > Bireysel
Psikotisizm	0.354±0.212	0.292±0.200	2.274	228	.024	0.300	Bireysel > Takım
Eysenck Kişilik Toplam Puanı	0.544±0.121	0.573±0.121	-1.780	228	.076	-0.235	Yok
Bedensel ve Bilişsel Kaygı	3.008±0.761	2.671±0.658	3.592	228	<.001	0.474	Bireysel > Takım
Güdülenme	3.810±0.795	3.760±0.822	0.475	228	.635	0.063	Yok
Kendine Güven	3.352±0.787	3.485±0.694	-1.366	228	.173	-0.180	Yok

Not: Bireysel sporcu n=112, takım sporcusu n=118.

Tablo 4 incelendiğinde, spor branşına göre nörotisizm, psikotisizm ve bedensel ve bilişsel kaygı değişkenlerinde anlamlı farklılıklar olduğu görülmektedir. Nörotisizm puanlarının takım sporcularında bireysel sporculara göre anlamlı düzeyde daha yüksek olduğu belirlenmiştir, t(228)=-2.530, p=.012. Psikotisizm puanlarının ise bireysel sporcularda takım sporcularına göre anlamlı düzeyde daha yüksek olduğu saptanmıştır, t(228)=2.274, p=.024. Bedensel ve bilişsel kaygı puanları incelendiğinde, bireysel sporcuların takım sporcularına göre anlamlı düzeyde daha yüksek kaygı düzeyine sahip oldukları görülmektedir, t(228)=3.592, p<.001. Cohen's d değerleri incelendiğinde, bu farklılıkların küçük ile orta düzey arasında etki büyüklüğüne sahip olduğu anlaşılmaktadır. Dışadönüklük, yalan/sosyal istenirlik, Eysenck kişilik toplam puanı, güdülenme ve kendine güven değişkenlerinde ise spor branşına göre anlamlı bir farklılık bulunmamıştır (p>.05).

Tablo 5. Sporculuk Durumuna Göre Bağımsız Örneklemler t-Testi Sonuçları

Değişken	Amatör Ort.±SS	Millî Ort.±SS	t	sd	p	Cohen's d	Anlamlı Fark
Dışadönüklük	0.570±0.284	0.556±0.274	0.319	228	.750	0.051	Yok
Yalan/Sosyal İstenirlik	0.658±0.267	0.605±0.292	1.241	228	.216	0.197	Yok
Nörotisizm	0.616±0.279	0.565±0.313	1.122	228	.263	0.178	Yok
Psikotisizm	0.301±0.203	0.399±0.208	-3.022	228	.003	-0.480	Millî > Amatör
Eysenck Kişilik Toplam Puanı	0.562±0.121	0.548±0.125	0.708	228	.479	0.112	Yok
Bedensel ve Bilişsel Kaygı	2.819±0.698	2.894±0.831	-0.651	228	.516	-0.103	Yok
Güdülenme	3.766±0.766	3.848±0.945	-0.639	228	.524	0.101	Yok
Kendine Güven	3.403±0.706	3.482±0.860	-0.668	228	.505	-0.106	Yok

Not: Amatör sporcu n = 179, milli sporcu n = 51.

Tablo 5 incelendiğinde, sporculuk durumuna göre yalnızca psikotisizm puanlarında istatistiksel olarak anlamlı bir farklılık bulunduğu görülmektedir, *t*(228)=-3.022, *p*=.003, Cohen's *d*=-0.480. Millî sporcuların psikotisizm puan ortalaması (0.399±0.208), amatör sporcuların puan ortalamasından (0.301±0.203) anlamlı düzeyde daha yüksektir. Cohen's *d* değeri, bu farklılığın küçük-orta düzeyde bir etkiye sahip olduğunu göstermektedir. Dışadönüklük, yalan/sosyal istenirlik, nörotisizm, Eysenck kişilik toplam puanı, bedensel ve bilişsel kaygı, güdülenme ve kendine güven puanlarında ise amatör ve millî sporcular arasında istatistiksel olarak anlamlı bir farklılık bulunmamıştır (*p*>.05).

Tablo 6. Değişkenler Arası Pearson Korelasyon Sonuçları

Değişkenler	1	2	3	4	5	6	7	8
1. Dışadönüklük	—							
2. Yalan/Sosyal İstenirlik	.046	—						
3. Nörotisizm	-.247***	-.028	—					
4. Psikotisizm	.195**	-.243***	-.156*	—				
5. Eysenck Kişilik Toplam Puanı	.578***	.482***	.378***	.272***	—			
6. Bedensel ve Bilişsel Kaygı	-.207**	.018	.204**	-.212**	-.058	—		
7. Güdülenme	.177**	.263***	-.046	-.245***	.125	.077	—	
8. Kendine Güven	.260***	.135*	-.143*	.001	.132*	-.234***	.589***	—

Not: N = 230. *p < .05, **p < .01, ***p < .001.

Tablo 6 incelendiğinde, dışadönüklük ile bedensel ve bilişsel kaygı arasında negatif yönde ve anlamlı bir ilişki olduğu görülmektedir (r=-.207, p=.002). Dışadönüklük ile güdülenme (r=.177, p=.007) ve kendine güven (r=.260, p<.001) arasında ise pozitif yönde ve anlamlı ilişkiler bulunmuştur. Buna göre dışadönüklük düzeyi yüksek olan sporcuların bedensel ve bilişsel kaygı düzeyleri daha düşük; güdülenme ve kendine güven düzeyleri ise daha yüksek olma eğilimindedir. Yalan/sosyal istenirlik ile bedensel ve bilişsel kaygı arasında anlamlı bir ilişki bulunmazken (r=.018, p=.788), yalan/sosyal istenirlik ile güdülenme (r=.263, p<.001) ve kendine güven (r=.135, p=.041) arasında pozitif yönde ve anlamlı ilişkiler saptanmıştır. Nörotisizm ile bedensel ve bilişsel kaygı arasında pozitif yönde ve anlamlı bir ilişki bulunmuştur (r=.204, p=.002). Nörotisizm ile kendine güven arasında ise negatif yönde ve anlamlı bir ilişki belirlenmiştir (r=-.143, p=.031). Buna karşılık nörotisizm ile güdülenme arasındaki ilişkinin istatistiksel olarak anlamlı olmadığı görülmüştür (r=-.046, p=.489). Psikotisizm ile bedensel ve bilişsel kaygı (r=-.212, p=.001) ve güdülenme (r=-.245, p<.001) arasında negatif yönde ve anlamlı ilişkiler bulunmuştur. Psikotisizm ile kendine güven arasında ise istatistiksel olarak anlamlı bir ilişki saptanmamıştır (r=.001, p=.991). Eysenck kişilik toplam puanı ile kendine güven arasında pozitif yönde, düşük düzeyde ve anlamlı bir ilişki bulunmuştur (r=.132, p=.045). Eysenck kişilik toplam puanının bedensel ve bilişsel kaygı (r=-.058, p=.379) ve güdülenme (r=.125, p=.059) ile ilişkileri ise istatistiksel olarak anlamlı değildir. Psikolojik performans bileşenleri arasındaki ilişkiler incelendiğinde, bedensel ve bilişsel kaygı ile kendine güven arasında negatif yönde ve anlamlı bir ilişki olduğu belirlenmiştir (r=-.234, p<.001). Güdülenme ile kendine güven arasında ise pozitif yönde ve anlamlı bir ilişki bulunmaktadır (r=.589, p<.001). Bedensel ve bilişsel kaygı ile güdülenme arasındaki ilişki istatistiksel olarak anlamlı değildir (r=.077, p=.246).

TARTIŞMA

Bu araştırmada sporcuların kişilik özellikleri ile psikolojik performans bileşenleri arasındaki ilişkiler ve bu değişkenlerin cinsiyet, spor branşı ve sporculuk düzeyine göre farklılaşıp farklılaşmadığı incelenmiştir. Cinsiyete değişkenine göre kadın sporcuların yalan/sosyal istenirlik ve toplam kişilik puanlarının erkek sporculardan daha yüksek, erkek sporcuların ise kendine güven düzeylerinin daha yüksek olduğu saptanmıştır. Spor branşı açısından takım sporcularının nörotisizm düzeyleri bireysel sporculara göre daha yüksek bulunurken, bireysel sporcuların psikotisizm ile bedensel ve bilişsel kaygı düzeylerinin daha yüksek olduğu belirlenmiştir. Sporculuk düzeyine göre ise yalnızca psikotisizm boyutunda anlamlı farklılık saptanmış ve millî sporcuların amatör sporculara göre daha yüksek psikotisizm puanlarına sahip olduğu görülmüştür. Korelasyon analizleri, dışadönüklüğün bedensel ve bilişsel kaygı ile negatif; güdülenme ve kendine güven ile pozitif ilişkili olduğunu ortaya koymuştur. Buna karşılık nörotisizm bedensel ve bilişsel kaygı ile pozitif, kendine güven ile negatif ilişki göstermiştir. Psikotisizm ise bedensel ve bilişsel kaygı ile güdülenme arasında negatif yönlü ilişki sergilerken, kendine güven ile anlamlı ilişki göstermemiştir. Ayrıca psikolojik performans bileşenleri arasında bedensel ve bilişsel kaygının kendine güven ile negatif, güdülenmenin ise kendine güven ile güçlü ve pozitif yönde ilişkili olduğu belirlenmiştir. Bu bulgular, kişilik özelliklerinin sporcuların psikolojik performansının farklı boyutlarıyla anlamlı düzeyde ilişkili olduğunu göstermektedir.

Araştırmada dışadönüklük kişilik özelliğinin bedensel ve bilişsel kaygı ile negatif, güdülenme ve kendine güven ile pozitif yönde ilişkili olduğu belirlenmiştir. Bu bulgu, dışadönük sporcuların performans ortamlarında daha olumlu psikolojik özellikler sergilediğini göstermektedir. Spor psikolojisi alanında yapılan kapsamlı derleme çalışmalarında dışadönüklüğün sporcuların psikolojik durumları, uzun dönem sportif başarıları ve performans süreçleriyle pozitif yönde ilişkili olduğu bildirilmektedir (Allen vd., 2013; Allen & Laborde, 2014). Ayrıca kişilik özellikleri üzerine yapılan çalışmalarda, dışadönüklüğün öz güven, olumlu duygulanım ve motivasyon gibi performansı destekleyen psikolojik özelliklerle ilişkili olduğunu göstermektedir (Laborde vd., 2020). Benzer şekilde, sporcuların kişilik özellikleri ile rekabet kaygıları arasındaki ilişkileri inceleyen sistematik bir derlemede dışadönüklüğün bilişsel ve bedensel kaygı ile negatif, kendine güven ile ise pozitif yönde ilişkili olduğu bildirilmiştir (Herinasari vd., 2025). Bu doğrultuda araştırmamızdan elde edilen bulgular, dışadönüklüğün sporcuların psikolojik performansını destekleyen önemli kişilik özelliklerinden biri olduğunu ortaya koyan önceki çalışmalarla paralellik göstermektedir.

Araştırmada nörotisizm kişilik özelliğinin bedensel ve bilişsel kaygı ile pozitif, kendine güven ile ise negatif yönde ilişkili olduğu belirlenmiştir. Bu bulgu, duygusal açıdan daha dengesiz sporcuların yarışma ortamlarında daha fazla kaygı yaşayabildiklerini ve performanslarına yönelik güvenlerinin daha

düşük olabildiğini düşündürmektedir. Amaro ve Brandão (2023), duygusal istikrarın bilişsel ve bedensel kaygı ile negatif, kendine güven ile ise pozitif yönde ilişkili olduğunu belirlemiştir. Duygusal istikrarın nörotisizmin karşıt kutbunu oluşturduğu dikkate alındığında, söz konusu sonuçlar araştırmamızdan elde edilen bulgularla paralellik göstermektedir. Benzer biçimde Herinasari vd. (2025) tarafından gerçekleştirilen sistematik derlemede, nörotisizmin bilişsel ve bedensel yarışma kaygısı ile pozitif, kendine güven ile ise negatif yönde ilişkili olduğu bildirilmiştir. Dai vd. (2026) ise kişilik özelliklerinin müsabaka performansı üzerindeki etkisinde rekabet kaygısının aracı bir rol üstlenebildiğini göstermiştir. Bu sonuçlar, nörotisizmin sporcuların kaygı ve kendine güven düzeyleriyle ilişkili önemli bir kişilik özelliği olduğunu ortaya koymaktadır. Araştırmada cinsiyete göre kadın sporcuların sosyal istenirlik ve toplam kişilik puanlarının erkek sporculardan daha yüksek, erkek sporcuların ise kendine güven düzeylerinin daha yüksek olduğu belirlenmiştir. Cinsiyet açısından elde edilen bu sonuç, kadın sporcuların bilişsel ve bedensel kaygı düzeylerinin, erkek sporcuların ise kendine güven düzeylerinin daha yüksek olduğunu gösteren Amaro ve Brandão'nun (2023) bulgularıyla paralellik göstermektedir. Buna karşın kadın sporcuların sosyal onay beklentisinin daha yüksek olabileceği ve bu durumun sosyal istenirlik puanlarını etkileyebileceği ifade edilmektedir (Karancı vd., 2007). Spor branşı açısından takım sporcularının nörotisizm düzeylerinin daha yüksek, bireysel sporcuların ise psikotisizm ile bedensel ve bilişsel kaygı düzeylerinin daha yüksek olduğu belirlenmiştir. Bireysel sporlarda performans sorumluluğunun doğrudan sporcunun kendisinde olması nedeniyle yarışma kaygısının takım sporlarına göre daha yüksek olabileceği belirtilmektedir (Craft vd., 2003). Öte yandan takım sporlarının sağladığı sosyal destek ve sorumluluğun paylaşılması, kaygı düzeyinin azalmasına katkı sağlayabilmektedir (Evans vd., 2012). Sporculuk düzeyi açısından ise yalnızca psikotisizm boyutunda anlamlı farklılık bulunmuş ve millî sporcuların amatör sporculara göre daha yüksek puan aldığı belirlenmiştir. Literatürde elit sporcuların kişilik özelliklerinin branş, rekabet düzeyi ve performans gereksinimlerine bağlı olarak farklılaşabileceği, özellikle üst düzey rekabet ortamlarının bazı kişilik özelliklerini belirginleştirebildiği belirtilmektedir (Piepiora, 2021; Laborde vd., 2016). Bu nedenle elde edilen bulguların farklı spor branşları ve elitlik düzeyleri dikkate alınarak değerlendirilmesi gerektiği düşünülmektedir.

Genel olarak değerlendirildiğinde, araştırmadan elde edilen bulgular Eysenck kişilik özelliklerinin sporcuların psikolojik performans bileşenleriyle anlamlı ilişkiler gösterdiğini ortaya koymaktadır. Özellikle dışadönüklük ve nörotisizm boyutlarının kaygı, güdülenme ve kendine güven üzerinde belirleyici rol oynadığı görülmektedir. Bu sonuçlar, kişilik özelliklerinin sportif performansın yalnızca fiziksel değil aynı zamanda psikolojik yönünün de önemli belirleyicilerinden biri olduğunu bildiren önceki araştırmalarla paralellik göstermektedir (Allen vd., 2013; Laborde vd., 2016; Piepiora, 2021). Bununla birlikte, psikotisizm ile bazı psikolojik performans bileşenleri arasındaki ilişkiler ve millî sporcuların daha yüksek psikotisizm puanına sahip olması gibi bulgular, literatürde sınırlı düzeyde ele alınmış olup farklı örneklemler üzerinde yeniden araştırılmaya ihtiyaç duyulduğunu göstermektedir. Bu yönüyle araştırmanın, sporcularda kişilik özellikleri ile psikolojik performans arasındaki ilişkinin daha kapsamlı anlaşılmasına katkı sağlayacağı düşünülmektedir.

SONUÇ

Bu araştırmada sporcuların Eysenck kişilik özellikleri ile psikolojik performans bileşenleri arasındaki ilişkiler incelenmiş, ayrıca bu değişkenlerin cinsiyet, spor branşı ve sporculuk düzeyine göre farklılaşıp farklılaşmadığı değerlendirilmiştir. Araştırma sonucunda dışadönüklüğün bedensel ve bilişsel kaygıyı azaltırken güdülenme ve kendine güveni desteklediği, nörotisizmin ise kaygıyı artırıp kendine güveni olumsuz etkilediği belirlenmiştir. Ayrıca cinsiyet, spor branşı ve sporculuk düzeyine göre bazı kişilik özellikleri ile psikolojik performans bileşenlerinde anlamlı farklılıklar olduğu saptanmıştır. Elde edilen bulgular, kişilik özelliklerinin sporcuların psikolojik performansını açıklamada önemli değişkenlerden biri olduğunu göstermektedir. Bu doğrultuda sporcuların psikolojik hazırlık süreçlerinde kişilik özelliklerinin dikkate alınması ve bireysel özelliklere uygun psikolojik beceri eğitimlerinin planlanması, performansın geliştirilmesine katkı sağlayabilir.

Araştırmanın Etik ve İzin Süreci

Bu çalışmada kullanılan verilerin toplanabilmesi için gerekli etik kurul onayı alınmıştır. Araştırmanın etik açıdan uygunluğu, Erzurum Teknik Üniversitesi Bilimsel Araştırma ve Yayın Etik Kurulunun 12.09.2024 tarihli, 10 toplantı sayılı ve 01 karar sayılı kararı ile onaylanmıştır.

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THE RELATIONSHIP BETWEEN FEAR OF MISSING OUT AND IN-GAME CONTENT PURCHASE MOTIVATIONS AMONG DIGITAL GAMERS

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ABSTRACT

Fear of missing out (FoMO) may help explain why opportunities to acquire virtual content become personally or socially meaningful to digital gamers. This study examines the association between personal and social FoMO and eight dimensions of in-game content purchase motivation among 500 digital gamers. The descriptive and correlational analysis uses the nine-item FoMO Scale and the 30-item In-Game Content Purchase Motivations Scale, with responses coded from 1 to 7. Descriptive statistics, internal consistency coefficients, Pearson correlations, Welch *t* tests, and one-way analyses of variance were calculated. Total FoMO correlated positively with total purchase motivation, $r = .608$, 95% CI [.550, .660]. The strongest association between individual dimensions involved social FoMO and social affiliation, $r = .685$. Personal FoMO was most strongly associated with achievement among the eight purchase facets, $r = .557$. Younger participants had higher FoMO and purchase motivation scores. Gender groups differed in purchase motivation but not FoMO. Purchase motivation varied across game genres, while both outcomes varied across platforms. Continuous-age, rank-correlation, alternative-scoring, and unequal-variance checks retained the principal patterns. The findings distinguish concerns about personal progress from concerns about social inclusion and indicate that FoMO is associated with several motives for purchasing virtual content. The correlational design does not establish causal effects. Further research should evaluate the measurement structure and examine these relationships using longitudinal designs and behavioral spending records.

Keywords: fear of missing out, digital gaming, virtual goods, purchase motivation, self-determination theory, social affiliation

INTRODUCTION

In-game purchasing links the organization of digital leisure to consumer decisions about virtual content. Players can obtain items that change performance, expand available choices, or alter how they appear to other people. The value of these purchases therefore depends partly on the activities and relationships in which they are used. Early research on virtual item sales distinguished functional benefits from aesthetic and social attributes, while subsequent work connected purchasing to players' evaluations of game items and the surrounding experience (Lehdonvirta, 2009; Park & Lee, 2011). An account based only on the physical absence of a product misses the meanings that virtual possessions can acquire within a game.

The motives for buying content also differ from the motives for playing. Enjoying a game does not necessarily create a reason to pay for an additional item, and continued use and purchase decisions can have different antecedents (Hamari, 2015; Hamari, Hanner, & Koivisto, 2017, 2020). A meta-analysis of virtual goods research likewise supports considering several motivational and contextual influences rather than assuming a single explanation of purchasing (Hamari & Keronen, 2017). This distinction matters for recreation research because an enjoyable activity can coexist with commercial pressures that affect how participation is organized and experienced.

Research on concrete purchase motivations has identified varied reasons for spending within games (Hamari, Alha, et al., 2017). Qualitative evidence further distinguishes functional, probability-based, and ornamental goods, with different purchase processes across these categories (Cai, Cebollada, & Cortiñas, 2022). Cosmetic items are particularly instructive: players may value them despite their limited or absent contribution to competitive performance (Marder et al., 2019). Consequently, motivation should be examined at a level that preserves differences between achievement, self-expression, and social connection.

Fear of missing out offers an additional perspective on these decisions. FoMO concerns the unease associated with being absent from valued experiences or opportunities. Foundational research connected

it to motivational needs, affect, and engagement with social media (Przybylski, Murayama, DeHaan, & Gladwell, 2013). Subsequent work examined its occurrence across everyday situations and its relationships with well-being (Milyavskaya, Saffran, Hope, & Koestner, 2018). Consumer research suggests that FoMO is also relevant to purchase likelihood, including responses to messages that emphasize potentially missed experiences (Good & Hyman, 2020, 2021). These findings make FoMO relevant to games in which participation, progression, and the availability of content are temporally organized.

However, a total FoMO score may obscure theoretically meaningful differences. A self-concept approach separates concerns about missed opportunities for the private self from concerns about exclusion or diminished standing in the social group (Zhang, Jiménez, & Cicala, 2020). These concerns need not have identical associations with every purchasing motive. Missing an opportunity to progress may be particularly relevant to achievement-oriented purchases, whereas missing a shared experience may be especially relevant to social affiliation. The present analysis uses this distinction alongside a recent multidimensional measure of in-game content purchase motivations (Hussain, Hollebeek, Marder, & Ting, 2025).

The study examines three questions: how personal, social, and total FoMO relate to purchase motivation; whether the association varies across purchase facets; and how the two total scores differ across age, gender, game genre, and platform categories in the study sample. Its purpose is to document these relationships precisely and develop an interpretation that can guide subsequent empirical investigation. The analysis concerns motivations to purchase content; it does not directly measure spending, conversion to paying status, problematic purchasing, or the effects of specific sales messages.

Theoretical background

FoMO research has often developed through the study of social media engagement. Associations with academic motivation and media engagement, problematic smartphone use, and Internet-communication symptoms indicate that the construct spans several forms of digitally mediated behavior (Alt, 2015; Elhai, Levine, Dvorak, & Hall, 2016; Wegmann, Oberst, Stodt, & Brand, 2017). Research on social media fatigue also places FoMO within a broader network of compulsive use and psychological strain (Dhir, Yossatorn, Kaur, & Chen, 2018). These findings establish a useful background, but they cannot be transferred directly to purchasing in games: communication frequency, purchase motivation, and financial expenditure are different outcomes.

The personal–social distinction addresses this contextual problem by grounding FoMO in threats to self-concept. Personal FoMO concerns the perceived significance of missed experiences for one's own life, goals, and opportunities. Social FoMO concerns how absence may affect acceptance and connection with others (Zhang et al., 2020). In a gaming context, the first may involve concerns about missed progress or desirable experiences; the second may involve concerns about losing access to shared activities or appearing disconnected from peers. These examples are theoretical applications rather than situations measured separately in the present dataset.

Social comparison provides a plausible bridge between these concerns and digital consumption. Individuals evaluate aspects of themselves in relation to others, especially when objective standards are unavailable (Festinger, 1954). Research has linked social comparison orientation and FoMO within explanations of social media engagement (Reer, Tang, & Quandt, 2019). In multiplayer environments, differences in visible possessions or progression could provide comparison cues. Nevertheless, visibility alone does not establish that a player feels threatened or purchases content in response. Perceived comparison, emotional response, and purchasing should be measured as separate processes.

A systematic review of FoMO research identified conceptual and contextual diversity and called for broader theoretical and methodological development (Tandon, Dhir, Almugren, AlNemer, & Mäntymäki, 2021). The present framework responds by distinguishing the two FoMO dimensions and examining their associations with specific motives. It does not assume that FoMO has the same meaning across all platforms, genres, or types of virtual goods.

Self-determination theory identifies autonomy, competence, and relatedness as fundamental psychological needs and distinguishes the quality of motivation from its intensity (Deci & Ryan, 2000; Ryan & Deci, 2000). Research applying this perspective to games has connected perceived autonomy and competence to enjoyment and motivation to continue playing (Ryan, Rigby, & Przybylski, 2006). A broader motivational model of game engagement likewise emphasizes the importance of experiences

that satisfy these needs (Przybylski, Rigby, & Ryan, 2010). This work helps explain why gaming can become a meaningful leisure activity, although satisfaction through play should not be equated with satisfaction through purchasing.

Other research reinforces the multidimensional character of participation. Motivations for online play include distinguishable achievement, social, and immersion components (Yee, 2006). Media enjoyment can also be understood partly through the satisfaction of psychological needs rather than momentary pleasure alone (Tamborini, Bowman, Eden, Grizzard, & Organ, 2010). These perspectives suggest that similar levels of overall engagement may reflect different motivational profiles and that those profiles may influence how players evaluate purchasable content.

The In-Game Content Purchase Motivations framework organizes eight facets under three broader domains: autonomy encompasses creativity, choice, and uniqueness; competence encompasses dominance, achievement, and skillfulness; relatedness encompasses social interaction and social affiliation (Hussain et al., 2025). This organization allows a more precise question than whether FoMO accompanies a general willingness to buy. It asks which purposes of purchasing covary with concerns about missed experiences.

Need-oriented purchase motives must also be distinguished from experienced need satisfaction. A strong desire to buy an item that promises inclusion does not establish that the purchase creates enduring connection. Recent measurement work in gaming explicitly separates need satisfaction and need frustration, providing a useful direction for future research (Ballou, Denisova, Ryan, Rigby, & Deterding, 2024). FoMO could be associated with aspirational consumption, a response to frustration, or both. The present measures cannot identify which account is correct.

There is a further measurement distinction. The IGCPM framework treats the broader domains and overarching construct formatively, while the individual facets have reflective indicators (Hussain et al., 2025). In a formative specification, components jointly define a construct and need not be interchangeable. Measurement scholarship warns against treating such components as if they were interchangeable manifestations of a single latent variable (Diamantopoulos & Winklhofer, 2001; Jarvis, MacKenzie, & Podsakoff, 2003). The total and higher-order scores used here are therefore transparent arithmetic summaries, not estimates of the original formative structural model.

Possessions can contribute to identity, and digital environments extend the settings in which this relationship operates (Belk, 1988, 2013). A virtual item may be valued because it supports an image, marks participation, or makes a character distinctive. Research on non-functional purchases illustrates why an item can matter even when it provides no measurable competitive advantage (Marder et al., 2019). This helps explain why uniqueness and affiliation belong alongside performance-related motives in the present analysis.

Belonging is also a basic interpersonal motivation (Baumeister & Leary, 1995). In games, the wish to interact with others and the wish to feel accepted by them are related but distinguishable. Social interaction concerns contact and communication; affiliation concerns inclusion and connection. A player may communicate frequently while remaining uncertain about acceptance. Theoretical alignment between social FoMO and affiliation therefore suggests a particularly close association, while also raising the possibility of overlapping item content.

Consumption-value research connects digital purchasing to the benefits users perceive in virtual items and communities (Kim, Gupta, & Koh, 2011). Work on young users of virtual worlds further shows the relevance of developmental and social contexts (Mäntymäki & Salo, 2015). In mobile games, perceived value and loyalty help explain purchase intention, and relationships may differ between paying and nonpaying users (Hsiao & Chen, 2016). These studies support examining the context of purchasing, while cautioning against treating age or platform categories as direct psychological explanations.

Scarcity can alter the perceived value of an opportunity, and limited-quantity and limited-time messages may operate differently (Aggarwal, Jun, & Huh, 2011; Lynn, 1991). Gaming systems such as battle passes organize access and rewards through ongoing participation, making time and progression part of the commercial context (Joseph, 2021). Such systems could make missed opportunities salient, but the current dataset contains no direct indicators of exposure to time-limited offers, battle passes, or notifications.

FoMO appeals are not guaranteed to increase purchasing. Experimental consumer research indicates that anticipated positive experiences and anticipated expense regret can operate in different directions (Good & Hyman, 2021). Accordingly, the present framework proposes a positive association between

FoMO and purchase motivation as an organizing expectation, while leaving room for avoidance, resistance, and budget constraints. It does not equate FoMO with a deterministic response to monetization.

The facet-level expectations are that personal FoMO will be closely associated with achievement-related motives and that social FoMO will be closely associated with affiliation-related motives. Demographic and gaming-context comparisons are exploratory. These expectations are not presented as preregistered confirmatory hypotheses.

MATERIALS AND METHODS

Design and participants

The study used a quantitative, descriptive, and correlational design to examine the relationships between fear of missing out and in-game content purchase motivations. The analyses included data from 500 digital gamers and examined differences according to age, gender, game genre, and gaming platform.

The dataset contained 39 item-level variables together with demographic characteristics and composite scores. All item values were integers between 1 and 7. No missing item responses or duplicate 39-item response vectors were detected. All 500 participants were retained in the analyses without imputation or exclusion. Composite scores were checked against their corresponding item means and agreed exactly for all ten first-order dimensions.

Participants were aged 18 to 40 years, with $M = 25.82$ and $SD = 4.65$. The sample included 355 male and 145 female participants. The main game-genre categories were first-person shooter (FPS), multiplayer online battle arena (MOBA), role-playing game (RPG), sports, and fighting. Platform categories were computer, console, and mobile. Country, income, gaming duration, purchase history, actual expenditure, and the identity of the principal game were unavailable for analysis.

Measures and scoring

FoMO was operationalized using the nine-item structure of Zhang et al. (2020): five personal FoMO items and four social FoMO items. Responses were coded from 1 (strongly disagree) to 7 (strongly agree), with no reverse-scored items. Each subscale was the mean of its items. Total FoMO was the mean of the personal and social subscale scores. Thus, the two dimensions contributed equally despite their unequal item counts. An alternative mean of all nine items was examined in a sensitivity analysis.

Purchase motivation followed the 30-item, eight-facet structure of Hussain et al. (2025). Creativity and choice each contained three items; uniqueness, dominance, achievement, skillfulness, social interaction, and social affiliation each contained four. Responses used the same 1–7 coding and required no reverse scoring. First-order facet scores were item means. Autonomy was the mean of creativity, choice, and uniqueness; competence was the mean of dominance, achievement, and skillfulness; relatedness was the mean of social interaction and social affiliation. The overall IGCPM score was the mean of all 30 items, which gives four-item facets more weight than three-item facets.

These scoring rules make the weighting of the dimensions and items explicit. No factor analysis, formative weighting estimation, or measurement invariance testing was performed. Total-score associations therefore concern the stated composite definitions. In particular, they do not establish that a single reflective factor explains all purchase items.

Statistical analysis

Means, standard deviations, skewness, and excess kurtosis described the score distributions. Cronbach's alpha was calculated from the item-level covariance structure for the first-order scales (Cronbach, 1951). Whole-instrument alpha values were also reported, but were not treated as evidence of unidimensionality or as validation of the higher-order formative model. This qualification follows established concerns about interpreting alpha without attention to measurement structure (Dunn, Baguley, & Brunsden, 2014; Sijtsma, 2009).

Pearson correlations summarized relationships between the three FoMO scores and the eight purchase facets, three domain composites, and overall purchase score. A Fisher-transformed 95% confidence interval was calculated for the principal total-score correlation. Two-sided Welch independent-samples *t* tests compared the age and gender groups; Welch's procedure avoids requiring equality of group variances (Delacre, Lakens, & Leys, 2017). The age grouping divided participants below and above the

sample mean, corresponding to ages 18–25 and 26–40. Because dichotomization discards information, correlations with continuous age were also calculated (MacCallum, Zhang, Preacher, & Rucker, 2002). One-way ANOVAs evaluated differences across game genres and platforms. For significant omnibus tests, all pairwise Welch comparisons within the corresponding factor–outcome family received Holm adjustment (Holm, 1979). The adjustment covered ten genre contrasts or three platform contrasts, respectively. Cohen's *d*, using the pooled standard deviation, described two-group differences, and eta squared described omnibus group effects (Lakens, 2013). The four binary comparisons and four omnibus tests were also considered together in a sensitivity check using Holm adjustment across these eight tests.

Additional sensitivity analyses used Spearman's rank correlation for the two totals, the nine-item FoMO mean in place of the equal-dimension composite, and Welch ANOVA for unequal-variance group comparisons. Conventional *p* values and confidence intervals are reported alongside effect sizes. Statistical significance was evaluated at the .05 level, with multiplicity adjustments applied as described above. These analyses estimate associations and group differences and do not establish causal effects. A *p* value does not measure effect size or practical importance (Wasserstein & Lazar, 2016).

RESULTS AND DISCUSSION

Participant characteristics and score distributions

Table 1 reports the demographic and gaming profile of the participants together with the two total-score means. Computer was the largest platform category (57.0%), and FPS was the largest genre category (36.0%). The age grouping was nearly balanced, with 247 participants below and 253 above the mean. These distributions are relevant to interpreting the precision of group comparisons, particularly those involving the smaller fighting-game category.

Table 1 *Demographic and gaming profile and total scores by group*

Variable	Category	*n*	%	FoMO *M* (*SD*)	IGCPM *M* (*SD*)
Age	18–25 years	247	49.4	4.50 (1.34)	4.35 (1.06)
	26–40 years	253	50.6	3.69 (1.33)	3.78 (1.12)
Gender	Male	355	71.0	4.11 (1.41)	4.16 (1.12)
	Female	145	29.0	4.05 (1.38)	3.81 (1.11)
Game genre	FPS	180	36.0	3.92 (1.46)	3.89 (1.15)
	MOBA	125	25.0	4.12 (1.41)	3.95 (1.17)
	RPG	80	16.0	4.12 (1.35)	4.15 (1.09)
	Sports	70	14.0	4.24 (1.26)	4.27 (1.00)
	Fighting	45	9.0	4.43 (1.38)	4.55 (0.99)
Platform	Computer	285	57.0	3.94 (1.39)	3.95 (1.09)
	Console	105	21.0	4.17 (1.42)	4.33 (1.11)
	Mobile	110	22.0	4.42 (1.35)	4.09 (1.19)

Note. $N = 500$. FPS = first-person shooter; MOBA = multiplayer online battle arena; RPG = role-playing game. Age groups reflect the split at the sample mean of 25.82 years. All scores range from 1 to 7.

Total FoMO averaged 4.09 ($SD = 1.40$), while total purchase motivation averaged 4.06 ($SD = 1.13$). The first-order scale means were close to the numerical midpoint of the response scale (Table 2). This description does not assign clinical or behavioral severity categories. Skewness and excess kurtosis for personal FoMO, social FoMO, and the two totals ranged from −.154 to .038 and from −.885 to −.505, respectively. These values did not indicate extreme marginal asymmetry, but do not prove multivariate normality.

Table 2 *Descriptive statistics and internal consistency*

Measure	Items	*M*	*SD*	α	Skewness	Kurtosis
Personal FoMO	5	4.05	1.47	.897	.038	−.885
Social FoMO	4	4.13	1.58	.916	−.154	−.835
Total FoMO	9	4.09	1.40	.927	−.055	−.777
Creativity	3	4.01	1.53	.822	.000	−.737
Choice	3	4.04	1.46	.802	−.033	−.758
Uniqueness	4	4.05	1.46	.864	−.044	−.812
Dominance	4	4.09	1.50	.874	.000	−.794
Achievement	4	4.04	1.52	.878	−.012	−.853
Skillfulness	4	4.06	1.51	.877	−.002	−.829
Social interaction	4	4.05	1.46	.864	−.077	−.740
Social affiliation	4	4.11	1.54	.893	−.071	−.823
Autonomy composite	10	4.03	1.19	—	−.089	−.531
Competence composite	12	4.06	1.28	—	−.019	−.643
Relatedness composite	8	4.08	1.36	—	−.112	−.695
Total IGCPM	30	4.06	1.13	.950	−.118	−.505

Note. N = 500. Higher scores indicate greater endorsement. No alpha coefficient is reported for the formative domain composites. Whole-instrument alpha does not establish unidimensionality. Domain item counts describe their component item sets; scoring uses the means specified in the Materials and methods section.

First-order alpha coefficients ranged from .802 for choice to .916 for social FoMO. Personal FoMO yielded α = .897. Whole-instrument coefficients were .927 for the nine FoMO items and .950 for the 30 purchase-motivation items. These coefficients describe item covariation in this dataset; the broader validity of the constructs requires separate evidence.

Associations between FoMO and purchase motivation

Total FoMO was positively associated with total purchase motivation, r = .608, 95% CI [.550, .660], p < .001. The squared correlation was approximately .370, indicating about 37.0% shared observed variance between the two composite scores. It does not represent a causal contribution or a forecast of spending. Personal and social FoMO correlated with total purchase motivation at r = .576 and r = .541, respectively. Their numerical difference was not subjected to a formal test of dependent correlations.

Table 3 *Pearson correlations between FoMO and purchase motivation*

Purchase dimension	Personal FoMO	Social FoMO	Total FoMO
Creativity	.300	.249	.298
Choice	.254	.219	.257
Uniqueness	.377	.435	.444
Dominance	.473	.356	.449
Achievement	.557	.426	.533
Skillfulness	.417	.259	.365
Social interaction	.455	.529	.538

Purchase dimension	Personal FoMO	Social FoMO	Total FoMO
Social affiliation	.542	.685	.671
Autonomy composite	.388	.375	.415
Competence composite	.571	.410	.531
Relatedness composite	.551	.672	.669
Total IGCPM	.576	.541	.608

Note. $N = 500$. All displayed correlations have $p < .001$ and remain below .001 after Holm adjustment across 36 tests. The total FoMO–IGCPM correlation has a Fisher-transformed 95% CI of [.550, .660].
All associations in Table 3 were positive. Among the eight purchase facets, social affiliation had the strongest relationship with social FoMO ($r = .685$) and with total FoMO ($r = .671$). Achievement had the strongest relationship with personal FoMO ($r = .557$), followed by social affiliation ($r = .542$). Creativity and choice showed smaller coefficients. At the broader domain level, personal FoMO was most closely associated with competence ($r = .571$), while social FoMO was most closely associated with relatedness ($r = .672$). All 36 correlations met $p < .001$ and remained below .001 after Holm adjustment across the full displayed family.

Age and gender comparisons

The lower-age group had higher total FoMO ($M = 4.50$, $SD = 1.34$) than the higher-age group ($M = 3.69$, $SD = 1.33$), $t(497.52) = 6.77$, $p < .001$, $d = 0.61$. Its total purchase motivation was also higher, $t(497.57) = 5.82$, $p < .001$, $d = 0.52$. Table 4 includes the mean differences and their intervals.

Table 4 *Welch t tests for age and gender groups*

Comparison and outcome	Group 1 *M* (*SD*)	Group 2 *M* (*SD*)	*t* (df)	*p*	*d*	Difference [95% CI]
Age Total FoMO	4.50 (1.34)	3.69 (1.33)	6.77 (497.52)	< .001	0.61	0.81 [0.58, 1.05]
Age Total IGCPM	4.35 (1.06)	3.78 (1.12)	5.82 (497.57)	< .001	0.52	0.57 [0.38, 0.76]
Gender Total FoMO	4.11 (1.41)	4.05 (1.38)	0.43 (272.26)	.670	0.04	0.06 [−0.21, 0.33]
Gender Total IGCPM	4.16 (1.12)	3.81 (1.11)	3.16 (270.42)	.002	0.31	0.35 [0.13, 0.56]

Note. Group 1 versus Group 2: ages 18–25 ($n = 247$) versus 26–40 ($n = 253$); male ($n = 355$) versus female ($n = 145$). Differences are Group 1 minus Group 2. *d* uses the pooled standard deviation; tests and difference intervals use Welch's unequal-variance procedure.
Male and female participants did not differ detectably in total FoMO, $t(272.26) = 0.43$, $p = .670$, $d = 0.04$. Total purchase motivation was higher in male participants, $t(270.42) = 3.16$, $p = .002$, $d = 0.31$. The small FoMO difference does not establish equivalence between groups; no equivalence test or measurement invariance assessment was conducted.

Game genre and platform comparisons

Total FoMO did not differ significantly across game genres, $F(4, 495) = 1.59$, $p = .176$, $\eta^2 = .013$. Purchase motivation did differ, $F(4, 495) = 4.32$, $p = .002$, $\eta^2 = .034$. Holm-adjusted pairwise comparisons showed higher purchase motivation in the fighting category than in FPS ($p = .002$) and MOBA ($p = .012$). Other genre contrasts did not meet the adjusted .05 threshold.

Table 5 *One-way ANOVA and adjusted pairwise comparisons*

Factor and outcome	*F* (df)	*p*	η²	Significant pairwise contrasts
Game genre Total FoMO	1.59 (4, 495)	.176	.013	None
Game genre Total IGCPM	4.32 (4, 495)	.002	.034	Fighting > FPS (.002); Fighting > MOBA (.012)
Platform Total FoMO	5.02 (2, 497)	.007	.020	Mobile > Computer (.005)
Platform Total IGCPM	4.46 (2, 497)	.012	.018	Console > Computer (.009)

Note. N = 500. Omnibus p values are unadjusted. Pairwise values use Holm adjustment within each significant factor–outcome family. The same six significant group results remained below .05 when Holm adjustment was applied across all eight binary and omnibus tests. Welch ANOVA sensitivity results are reported in the text.

Platform differences were present for total FoMO, $F(2, 497) = 5.02$, $p = .007$, $\eta^2 = .020$, and purchase motivation, $F(2, 497) = 4.46$, $p = .012$, $\eta^2 = .018$. Participants using mobile platforms had higher FoMO than participants using computers (Holm-adjusted $p = .005$). Participants using consoles had higher purchase motivation than participants using computers (Holm-adjusted $p = .009$). The omnibus effects accounted for relatively small proportions of total score variance.

Sensitivity analyses

Retaining age as a continuous variable yielded negative correlations with FoMO, $r = -.255$, $p < .001$, and purchase motivation, $r = -.185$, $p < .001$. The total-score Spearman correlation was $\rho = .595$, $p < .001$. Replacing equal dimension weighting with the mean of all nine FoMO items produced $r = .610$ with purchase motivation, $p < .001$. These checks preserved the direction and approximate magnitude of the principal relationships.

Welch ANOVA retained the genre result for purchase motivation, $F(4, 181.16) = 4.83$, $p = .001$, and the platform results for FoMO, $F(2, 218.34) = 5.16$, $p = .006$, and purchase motivation, $F(2, 212.86) = 4.53$, $p = .012$. Genre differences in FoMO remained nonsignificant, $p = .186$. Applying Holm adjustment across the eight binary and omnibus tests retained all six initially significant results at .05. The principal findings remained consistent across these analytical choices.

DISCUSSION

The principal numerical finding is a positive association between FoMO and motivations to purchase in-game content. This pattern is conceptually compatible with consumer research linking concerns about missed opportunities to purchase likelihood (Good & Hyman, 2020, 2021). In games, valued opportunities can involve progress, self-expression, or participation with others. FoMO may therefore be relevant to several purposes that players associate with virtual purchases. The findings support examining personal and social concerns separately, while the correlational design does not establish the causal mechanisms underlying these relationships.

Purchase motivation remains distinct from observed consumption. Research differentiating game enjoyment, continued use, and premium purchase intentions shows why an emotional or motivational relationship cannot be translated directly into a revenue outcome (Hamari, 2015; Hamari et al., 2020). An individual may endorse several reasons for acquiring content but refrain from spending because of price, competing priorities, dissatisfaction with monetization, or access through play. The absence of transaction records, disposable income, and prior purchasing in the dataset leaves these possibilities unresolved.

The observed r^2 likewise requires careful interpretation. Shared variance between two summary scores may include substantive overlap, common response tendencies, and features of their construction. It does not mean that FoMO explains 37% of actual spending. Using the same assessment method for all variables can introduce additional sources of covariance, highlighting the importance of design-based remedies and explicit measurement evaluation (Podsakoff, MacKenzie, Lee, & Podsakoff, 2003).

The facet-level pattern is more informative than the overall coefficient alone. Personal FoMO's strongest purchase-facet relationship involved achievement. A plausible interpretation is that concerns about missed opportunities align with the wish to progress or accomplish valued tasks. This reading is consistent with motivational accounts of gaming in which competence and advancement matter (Przybylski et al., 2010; Ryan et al., 2006; Yee, 2006). It remains a hypothesis about a process: neither perceived loss of progress nor the timing of a subsequent purchase was observed here.

Social FoMO was most closely associated with social affiliation. This is theoretically plausible because fear of exclusion and the wish to feel connected address neighboring aspects of interpersonal experience. Belonging theory provides a basis for investigating such a relationship (Baumeister & Leary, 1995). Digital possessions may also carry identity-relevant or socially legible meanings (Belk, 2013). A future study could examine whether items communicate group membership and whether that visibility changes the association between exclusion concerns and purchase decisions.

The same proximity raises a discriminant-validity question. Some social FoMO and affiliation items both concern being included or excluded. A high correlation could reflect overlapping content as well as a substantive relationship between distinct processes. Researchers should examine the item wording, compare measurement models, and assess whether social FoMO predicts behavior beyond affiliation motives. The current analysis neither estimated those models nor established incremental predictive validity.

Autonomy-oriented facets generally had weaker associations with FoMO. Creative expression and choice may reflect enjoyment or personal preference without requiring anxiety about missed opportunities. The observed distinction supports retaining separate facets when designing future tests, rather than assuming that every purchase motive responds similarly to FoMO. It also reinforces the difference between wanting to satisfy a need and actually experiencing its satisfaction (Ballou et al., 2024).

The age pattern persisted when age was analyzed continuously, so it was not solely an artifact of the mean split. Nevertheless, the split provides a less informative description than the original age variable, and should not be adopted as a substantive boundary between types of gamers (MacCallum et al., 2002). Future research could consider nonlinear age relationships and developmental context. Findings on adolescent virtual consumption may help formulate questions, but cannot establish the corresponding mechanisms in adults aged 18–40 (Mäntymäki & Salo, 2015).

The gender comparison suggests that similar total FoMO scores can coexist with different purchase-motivation scores. It therefore gives no basis for explaining the purchase difference through FoMO alone. Income, time spent playing, game selection, familiarity with monetization, and item preferences could help account for these differences. These variables were not available, and neither adjusted group effects nor mediated relationships were estimated. The two-category coding also cannot represent the full range of gender identities.

Genre and platform effects were small relative to within-category variation. Broad genre labels do not specify a common commercial system. Different games within the same genre may offer cosmetics, competitive advantages, expansions, or randomized rewards. Work distinguishing types of in-game goods makes this heterogeneity especially relevant (Cai et al., 2022). Similarly, platform differences may reflect selection of games and audiences rather than an effect of the device itself. Evidence on mobile-game loyalty and perceived value offers potential explanatory variables for future research (Hsiao & Chen, 2016).

The fighting-game and console contrasts should therefore be treated as descriptions of the groups in this sample. They do not justify population rankings, claims about stronger commercial susceptibility, or platform-specific causal recommendations. Replication with documented game titles, purchasing histories, and balanced recruitment would be necessary before such interpretations could be evaluated.

The conceptual framework directs attention to how commercial systems intersect with the experience of leisure. Content that supports expression, mastery, or social connection may have legitimate experiential value. However, purchase opportunities can also be presented through pressure, uncertainty, or repeated expenditure. Research on player-perceived unfair monetization identifies concerns that extend beyond a single transaction and into game design, advertising, currency systems, and competitive advantages (Petrovskaya & Zendle, 2022).

These concerns warrant distinguishing product categories. Loot-box research has identified gambling-like structural features and associations between loot-box purchasing and problem gambling

(Drummond & Sauer, 2018; Zendle & Cairns, 2018). Those findings do not make every virtual purchase equivalent to gambling, and the present data cannot identify exposure to randomized rewards. They do show why purchase-motivation research should record what is bought and how the transaction operates before interpreting consumer risks.

Limitations and future research

The correlational design limits conclusions about causal direction and the processes linking FoMO to purchase motivation. Higher FoMO may accompany stronger purchase motives, but the analyses cannot determine which develops first or whether other variables contribute to both. The sample was restricted to gamers aged 18–40, which limits generalization to younger and older populations. In addition, the absence of transaction records means that the findings concern purchase motivation rather than actual expenditure.

Measurement limitations also constrain interpretation. The analysis used composite means and alpha coefficients without estimating the original hierarchical measurement structure. Alpha cannot establish factorial validity, and high whole-instrument consistency does not resolve reflective–formative specification questions (Jarvis et al., 2003; Sijtsma, 2009). Further research should evaluate the two FoMO dimensions, the eight IGCPM facets, and the proposed higher-order components before interpreting structural relationships. Reliability estimates appropriate to the fitted measurement model and tests of measurement invariance would strengthen group comparisons (Dunn et al., 2014).

The theoretical processes remain unobserved. Future studies could measure perceived scarcity, anticipated regret, social comparison, and exposure to shared events. A longitudinal design could establish whether FoMO precedes changes in purchasing, while experiments could manipulate offer availability or social visibility without assuming that these features operate identically (Aggarwal et al., 2011; Good & Hyman, 2021). Behavioral records would help distinguish endorsed motives from transactions and permit separate examination of cosmetic, functional, and randomized purchases.

Finally, future sampling should document eligibility, recruitment channels, language, country, and participation rates. The analysis plan should define primary outcomes and multiplicity adjustments before inspecting results. Demographic comparisons should preserve continuous variables where possible and address game-level clustering when players are recruited from identifiable communities. These steps would strengthen the generalizability of the findings and clarify the conditions under which the observed relationships are reproduced.

CONCLUSION AND RECOMMENDATIONS

The findings show a positive association between FoMO and in-game content purchase motivation, with a prominent social FoMO–affiliation relationship and an achievement-oriented pattern for personal FoMO. The distinction between personal and social concerns is useful for understanding digital consumption within leisure. The analysis also demonstrates why scoring decisions, the formative structure of purchase motivations, and differences between motives and actual behavior must remain explicit. Longitudinal research, further measurement evaluation, and behavioral validation are needed to assess the direction, stability, and practical implications of these relationships.

Managerial recommendations should follow that specificity. Clear real-money prices, understandable availability periods, purchase histories, and optional spending controls can help users evaluate decisions. Socially meaningful experiences should remain accessible without presenting purchase as a condition for acceptance. These proposals align with work on predatory monetization and practical social responsibility (King & Delfabbro, 2018, 2019); their effectiveness was not tested here. In particular, the findings do not justify targeting people with higher FoMO using more urgent or exclusion-oriented messages.

For recreation education, the material can support discussions about how a freely chosen leisure activity becomes intertwined with ongoing consumption. The relevant question is whether purchasing supports the experience the player values and whether the choice remains understandable and manageable. Future evaluations should include perceived autonomy, enjoyment, regret, and financial consequences alongside conversion or retention outcomes.

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PRIVATE HIGH SCHOOL TEACHERS' VIEWS ON LEAVING THEIR JOBS

ÖZEL LİSELERDE ÇALIŞAN ÖĞRETMENLERİN İŞTEN AYRILMA DURUMLARINA İLİŞKİN GÖRÜŞLERİ

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Abstract
The aim of this study is to explore the views of teachers working in private high schools regarding leaving their jobs. A case study design, one of the qualitative research designs, was employed in the study. The study group consisted of 12 high school teachers who left their jobs while working at private high schools located in the central districts of Mersin during the 2024–2025 academic year. The study group was selected using homogeneous sampling, a purposive sampling technique. The researcher developed a "Semi-Structured Interview Form," which was used to collect the study data. The interview form was submitted to subject-matter experts for evaluation in terms of comprehensibility and clarity. Based on expert feedback and the results of a pilot study, the interview form was finalized. Content analysis was employed to analyze the qualitative data. Two researchers independently examined the participants' responses to the interview questions, identified codes, and grouped codes with similar characteristics to generate themes and subthemes. The reliability of the analysis was calculated using the formula "Reliability = Agreement / (Agreement + Disagreement) × 100." The inter-researcher reliability coefficient was found to be 86%. According to the findings, the vast majority of the participants (f = 10) reported that they had previously considered leaving their jobs. The reasons identified for leaving their jobs included "delayed salary payments, non-payment of salaries, finding a higher-paying job in another sector, negative attitudes and behaviors of parents, disrespectful behavior by students, workplace mobbing by school administrators, feelings of professional burnout, and difficulty adapting to the school culture." The participants reported that the consequences of leaving their jobs included "depression, financial hardship, conflicts with family members, distress, emotional exhaustion, illness, loss of self-confidence, marital breakdown, social exclusion, reduced well-being, self-blame, seeking employment in other sectors, and difficulties in starting a family." Based on the findings, it is recommended that policies be developed to improve teachers' working conditions in private schools and mitigate the economic, managerial, and psychosocial problems that contribute to teachers leaving their jobs.
Keywords: Teachers, Job Leaving, Private High Schools

Özet
Bu araştırmanın amacı, özel liselerde çalışan öğretmenlerin işten ayrılma durumlarına ilişkin görüşlerini tespit etmektir. Bu araştırmada nitel araştırma desenlerinden durum çalışması kullanılmıştır. Araştırmanın çalışma grubu, 2024-2025 eğitim-öğretim yılında Mersin merkez ilçelerindeki özel liselerde çalışırken işlerinden ayrılan 12 lise öğretmeninden oluşmaktadır. Amaçlı örnekleme yöntemlerinden benzeşik örneklem tekniği ile araştırmanın çalışma grubu belirlenmiştir. Araştırmacı "Yarı Yapılandırılmış Görüşme Formunu" kendisi geliştirmiştir ve çalışmanın verileri bu form ile toplanmıştır. Veri toplamak için kullanılan bu görüşme formu, anlaşılırlık ve açıklık açısından alan bilgisi uzmanlarının görüşlerine sunulmuştur. Uzman görüşü doğrultusunda ve pilot çalışma neticesinde görüşme formuna son şekli verilmiştir. Nitel aşamada verilerin analizi için içerik analizi yöntemi kullanılmıştır. İki araştırmacı, katılımcıların sorulara verdikleri cevapları bağımsız olarak incelemiş, kodlar belirlemiş ve benzer özelliklere sahip kodlar bir araya getirilerek temalar ve alt temalar oluşturulmuştur. Araştırmanın güvenirliği, "Güvenirlik = Görüş birliği / (Görüş birliği + Görüş ayrılığı) x 100" formülü ile tespit edilmiştir. Araştırmacılar arasındaki güvenirlik oranı %86 olarak tespit edilmiştir. Araştırma bulgularına göre, katılımcıların büyük çoğunluğu (f=10) daha önce işten ayrılma niyetine sahip olduklarını ifade etmiştir. Çalışmada, "maaşı zamanında alamama, maaşı hiç alamama, başka bir sektörde daha yüksek gelirli iş bulma, velilerin olumsuz tutum ve davranışları, öğrencilerin saygısızlığı, okul yöneticilerinin mobbing uygulaması, meslekte tükenmişlik hissi, okul kültürüne uyum

sağlayamama" katılımcıların işten ayrılma nedenleri olarak belirlenmiştir. Katılımcılar, "depresyon, geçim sıkıntısı, aile üyeleriyle tartışma, huzursuzluk, yıpranmışlık, hastalanma, özgüven kaybı, evliliğin sona ermesi, sosyal dışlama, refah düzeyinin azalması, kendini suçlama, başka sektörlerde iş arama, aile kuramama" gibi durumların işten ayrılma durumlarının sonuçları olduğunu ifade etmiştir. Araştırma bulguları doğrultusunda, özel okullarda öğretmenlerin çalışma koşullarının iyileştirilmesi ve işten ayrılmaya yol açan ekonomik, yönetsel ve psikososyal sorunların azaltılmasına yönelik politikaların geliştirilmesi önerilmektedir.
.**Keywords:** Öğretmenler, İşten Ayrılma, Özel Liseler

DEVELOPMENT OF THE INCLUSIVE EDUCATION TEXTBOOK ANALYSIS FORM: A DESIGN AND DEVELOPMENT RESEARCH

KAPSAYICI EĞİTİM İLKELERİ TEMELİNDE DERS KİTABI İNCELEME FORMUNUN GELİŞTİRİLMESİ: BİR TASARIM VE GELİŞTİRME ARAŞTIRMASI

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Abstract
The global educational goal of the 20th century was to ensure access to basic education for every individual, thereby increasing countries' literacy rates. This target was largely achieved by the last quarter of the 20th century. By the 1990s, however, it became clear that providing access to education alone was insufficient; the importance of educational content, quality, and the capacity of education to respond to individual and societal needs gained recognition. Consequently, international organizations such as UNESCO and UNICEF introduced the 21st-century goal for a new global education target: "Quality and Inclusive Education." Inclusive education refers to the execution of teaching-learning processes tailored to the interests and needs of all individuals, regardless of gender, ethnicity, religion, language, socio-economic status, or special needs. Numerous factors influence the realization of inclusive education, including national/international regulations, curriculum design, teacher training, instructional programs, learning environments, teaching-learning processes, and assessment and evaluation methods. One of these critical factors is the use of textbooks as instructional content. Structuring textbooks to support inclusiveness is crucial for helping students internalize and conceptualize it. However, a review of the literature on inclusive education in textbooks reveals that inclusivity is often reduced to gender and disability issues. In this context, the aim of this study is to develop a valid and reliable "Inclusive Education Textbook Analysis Form" that enables a multidimensional evaluation of textbooks in accordance with UNESCO's definition of inclusive education and the principles established in the literature. The study was conducted using the design and development research model, which aims to produce a functional evaluation tool. This research presents the development process and content of the form, along with the results of its pilot application to the 7th-grade Social Studies textbook prepared under the Century of Türkiye Education Model (TYMM). The developed "Inclusive Education Textbook Analysis Form" is intended to serve as a reference source for evaluating textbooks across all educational levels.
Keywords: Inclusive Education, Textbook Analysis Form, Design and Development Research, Century of Türkiye Education Model, Social Studies Textbook.

Özet
20. yüzyılın küresel eğitim hedefi her bireyin temel eğitime erişiminin sağlanarak ülkelerin okuryazar oranlarını artırılmasıydı. Bu hedefe 20. yüzyılın son çeyreği itibariyle büyük oranda erişilmiştir. 1990'lı yıllara gelindiğinde ise yalnızca eğitime erişim sağlamanın yeterli olmadığı; eğitimin içeriği, niteliği, bireysel ve toplumsal gereksinimlere yanıt verme kapasitesinin önemi de anlaşılmaya başlanmıştır. Dolayısıyla UNESCO ve UNICEF gibi uluslararası kuruluşlar yeni bir küresel eğitim hedefi için 21. yüzyılın hedefini "Nitelikli ve Kapsayıcı Eğitim" olarak ortaya koymuşlardır. Kapsayıcı eğitim; cinsiyet, etnik köken, din, dil, sosyo-ekonomik düzey ve özel gereksinimler gözetilmeksizin tüm bireylerin ilgi ve gereksinimlerine göre öğrenme-öğretme süreçlerinin yürütülmesidir. Kapsayıcı eğitimin gerçekleşebilmesi için ulusal/uluslararası mevzuatlar, müfredat anlayışı, öğretmen eğitimi, öğretim programı, öğrenme ortamı, öğrenme-öğretme süreci ve ölçme-değerlendirme gibi pek çok faktör etkilidir. Bu faktörlerden biri de içerik olarak ders kitaplarıdır. Ders kitapları kapsayıcılığı destekleyici şekilde yapılandırılması öğrencilerin kapsayıcılığı somutlaştırması açısından önemlidir.

Ancak alanyazında ders kitaplarında kapsayıcı eğitimi inceleyen çalışmalar incelendiğinde kapsayıcı eğitimi daha çok cinsiyet ve engellilik üzerine basit şekilde indirgendiği görülmektedir. Bu bağlamda araştırmanın amacı UNESCO'nun kapsayıcı eğitim tanımına ve alanyazında yer alan kapsayıcı eğitimin ilkelerine uygun şekilde ders kitaplarını çok boyutlu değerlendirmeyi sağlayacak geçerli ve güvenilir bir "Kapsayıcı Eğitim Ders Kitabı İnceleme Formu" geliştirmektir. Araştırma, işlevsel bir değerlendirme aracı ortaya koymayı hedefleyen tasarım ve geliştirme araştırması modeline göre yürütülmüştür. Bu araştırmada formun geliştirilme süreci, içeriği ve Türkiye Yüzyılı Maarif Modeli (TYMM) ile hazırlanan 7. sınıf Sosyal Bilgiler ders kitabı üzerindeki pilot uygulamasına yönelik sonuçlara yer verilmiştir. Geliştirilen "Kapsayıcı Eğitim Ders Kitabı İnceleme Formu"nun tüm eğitim kademelerindeki ders kitaplarının incelenmesinde yararlanılacak bir referans kaynağı olması hedeflenmektedir.

Anahtar kelimeler: Kapsayıcı Eğitim, Ders Kitabı İnceleme Formu, Tasarım ve Geliştirme Araştırması, Türkiye Yüzyılı Maarif Modeli, Sosyal Bilgiler Ders Kitabı.

THE PARENTING STYLES PREDICTING IMAGES OF GOD

TANRI İMAJINI YORDAYAN EBEVEYNLİK BİÇİMLERİ

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Abstract
Previous research examining the psychological factors involved in the construction of the God image—which expresses the individual's personal, emotional, and subjective relationship with God—has focused on attachment, childhood traumas, self-esteem, and parental images. Young's Schema Theory, which addresses attachment patterns, experiences of neglect and abuse, and other early parent-child interactions within the context of the child's universal needs, provides a more comprehensive framework for understanding the role of early parent-child relationships in the development of the God image. Therefore, this study investigated the relationship between parenting styles defined within the framework of Young's Schema Theory and the God image. Data were obtained from 591 university students who believe in Islam, using a Demographic Information Form, the Young Parenting Inventory, and the God Image Scale. To identify the parenting styles that predict the God image, Hierarchical Multiple Regression Analysis was conducted while controlling for demographic variables (age, gender, education level, and monthly family income). The findings showed that Overbearing/Achievement-Oriented parenting for both mothers and fathers positively and significantly predicted the Fearful God image. In addition, Overprotective/Anxious and Pessimistic/Worried mothering, as well as Exploitative/Abusive fathering, positively and significantly predicted the Uninvolved God image. For both mothers and fathers, Emotionally Depriving and Exploitative/Abusive parenting negatively and significantly predicted the Loving God image. Unexpectedly, Unchanging/Emotionally Inhibited fathering positively predicted the Loving God image. Finally, the relational pattern observed between the Loving God image and parenting styles was found to be identically replicated for the Balanced God image. The findings were discussed within the context of religious education, spiritual counseling, and schema-based clinical applications, and directions for future research were presented
Keywords: Parenting Styles, God Image, Loving God Image, Uninvolved God Image, Fearful God Image

Özet
Bireyin tanrı ile kişisel, duygusal ve öznel ilişkisini ifade eden tanrı imajının kurulumunda rol oynayan psikolojik faktörleri inceleyen önceki araştırmaların bağlanma, çocukluk çağı travmaları, benlik saygısı ve ebeveyn imgesine odaklandığı görülmektedir. Bağlanma örüntüleri, ihmal-istismar yaşantıları ve diğer erken dönem ebeveyn-çocuk etkileşimlerini, çocuğun evrensel ihtiyaçları bağlamında ele alan Young'ın Şema Kuramı erken dönem ebeveyn –çocuk ilişkisinin tanrı imajının gelişimindeki rolünü anlamada daha kapsamlı bir çerçeve sunmaktadır. Bu nedenle bu araştırmada, Young Şema Kuramı çerçevesinde tanımlanan ebeveynlik biçimleri ile tanrı imajı arasındaki ilişki incelenmiştir. Araştırmanın verileri, Demografik Bilgi Formu, Young Ebeveynlik Ölçeği ve Tanrı Tahayyülleri Ölçeği kullanılarak, İslam dinine inanan 591 üniversite öğrencinden elde edilmiştir. Tanrı imajını yordayan ebeveynlik biçimlerini tespit etmek için, demografik değişkenler (yaş, cinsiyet, eğitim düzeyi ve aylık aile geliri) kontrol edilerek Hiyerarşik Çoklu Regresyon Analizi yapılmıştır. Bulgular, hem anne hem de baba için Koşullu/Başarı odaklı ebeveynlik biçiminin Korkutan Tanrı imajını pozitif yönde ve anlamlı olarak yordadığını göstermiştir. Ayrıca, Aşırı Koruyucu/Evhamlı ve Kötümser/Endişeli anneliğin; Sömürücü/İstismar Edici babalığın İlgisiz Tanrı imajını pozitif yönde ve anlamlı olarak yordadığı gözlenmiştir. Hem anne hem de baba için, Duygusal Bakımdan Yoksun Bırakıcı ve Sömürücü/İstismar Edici Ebeveynliğin, Seven Tanrı imajını negatif yönde anlamlı olarak yordadığı görülmüştür. Beklenmedik bir şekilde Değişime Kapalı/Duygularını Bastıran babalığın seven tanrı imajını pozitif yönde yordadığı gözlenmiştir. Son olarak Seven Tanrı imajı ile ebeveynlik biçimleri arasında gözlenen ilişki örüntüsünün Dengeli Tanrı imajında da aynen tekrar ettiği gözlenmiştir.

Bulgular, din eğitimi, manevi danışmanlık, şema temelli klinik uygulamalar bağlamında tartışılmış ve yeni araştırma önerileri sunulmuştur.
Anahtar kelimeler: Ebeveynlik Biçimleri, Tanrı İmajı, Seven Tanrı İmajı, İlgisiz Tanrı İmajı, Korkutan Tanrı İmajı

KIRIM-KONGO KANAMALI ATEŞİNDE ACİL SERVİS HEMŞİRELİĞİNE YÖNELİK KANITA DAYALI GÜNCEL YAKLAŞIMLAR

EVIDENCE-BASED CURRENT APPROACHES TO EMERGENCY NURSING IN CRIMEAN CONGO HEMORRHAGIC FEVER

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ÖZET

Kırım-Kongo Kanamalı Ateşi (KKKA), Nairovirus kaynaklı, hızla dissemine intravasküler koagülasyon ve multiorgan yetmezliğine ilerleyebilen, %3-30 arasında değişen mortalite oranlarıyla acil sağlık sistemleri üzerinde ciddi bir tehdit oluşturan zoonotik bir enfeksiyondur. Hastalığın geniş klinik spektrumu ve hemorajik döneme ilerleme potansiyeli, acil servis hemşirelerinin erken tanı ve vaka yönetimi süreçlerinde yetkinliklerini kanıt temelli stratejilerle desteklemelerini zorunlu kılmaktadır.

Bu derlemenin amacı Kırım Kongo Kanamalı Ateşi'nin klinik seyri ve bulaş dinamiklerine yönelik güncel literatür, hemşirelik bakımında standart protokollerin acil servisteki hayati rolünü ortaya koymaktadır. Bu noktada, Hyalomma cinsi kenelerin taşıdığı Bunyaviridae ailesine mensup virüsün bulaş yollarının ve hastalık evrelerinin multidisipliner bir yaklaşımla kavranması, hemşirelerin enfeksiyon kontrolünde proaktif bir strateji geliştirmelerini zorunlu kılmaktadır. Hastalığın erken evrede hematolojik bulgularla (trombositopeni ve lökopeni) seyretmesi, acil servis hemşirelerinin vaka tanımlama ve izolasyon süreçlerinde hızlı klinik karar verme yetkinliklerini hayati bir öneme taşımaktadır. Simülasyon temelli uygulamalar, sağlık personelinin yüksek stres altındaki karar verme süreçlerini iyileştirerek, teorik bilginin pratik becerilere dönüştürülmesinde ve güvenli çalışma ortamlarının oluşturulmasında kanıtlanmış bir etkinlik sunmaktadır. Simülasyon eğitimiyle desteklenen pratik deneyimler, hemşirelerin enfeksiyon hastalıkları gibi stresli klinik senaryolarda öz-yeterlilik algısını artırarak, gerçek vaka yönetimindeki kaygı düzeylerini minimize etmektedir. Kırım Kongo Kanamalı Ateşi'nin hematojen ve temas yoluyla bulaşma riski göz önüne alındığında, acil servis hemşirelerinin vaka tanımlama ve izolasyon protokollerini uygulama konusundaki yetkinliklerinin güncel simülasyon deneyimleriyle periyodik olarak pekiştirilmesi, kurum içi enfeksiyon zincirini kırmada hayati bir rol oynamaktadır.

Gelecekteki hemşirelik uygulamalarında, simülasyon eğitimlerinin klinik çıktı üzerindeki etkisini izleyen boylamsal araştırmaların yaygınlaştırılması, enfeksiyon kontrolünde standardizasyonu sağlamak adına kritik bir gereksinimdir.

Anahtar kelimeler: Acil Hemşireliği, Kırım-Kongo Kanamalı Ateşi, Kene, Simülasyon

ABSTRACT

Crimean-Congo Hemorrhagic Fever (CCHF) is a zoonotic infection caused by Nairovirus that poses a serious threat to emergency healthcare systems, with mortality rates ranging from 3% to 30% and the potential to rapidly progress to disseminated intravascular coagulation and multiorgan failure. The broad clinical spectrum of the disease and its potential progression to the hemorrhagic phase require emergency nurses to support their competencies in early diagnosis and case management with evidence-based strategies.The aim of this review is to highlight the current literature on the clinical course and transmission dynamics of CCHF demonstrates the vital role of standardized protocols in emergency nursing care. At this point, understanding the transmission routes and disease stages of the virus carried by Hyalomma ticks and belonging to the Bunyaviridae family from a multidisciplinary perspective requires nurses to develop a proactive strategy for infection control. The occurrence of hematological

findings, particularly thrombocytopenia and leukopenia, in the early stage of the disease makes rapid clinical decision-making competence vital for emergency nurses during case identification and isolation. Simulation-based practices have demonstrated effectiveness in improving decision-making under high stress, translating theoretical knowledge into practical skills, and creating safe working environments. Practical experiences supported by simulation training further increase nurses' self-efficacy in stressful clinical scenarios such as infectious diseases and minimize anxiety during the management of real cases. Given the hematogenous and contact transmission risks associated with CCHF, periodically reinforcing emergency nurses' competence in case identification and implementation of isolation protocols through up-to-date simulation experiences plays a vital role in breaking the chain of infection within healthcare institutions.

In future nursing practice, expanding longitudinal research that monitors the effects of simulation training on clinical outcomes is a critical requirement for achieving standardization in infection control.

Keywords: Emergency Nursing, Crimean-Congo Hemorrhagic Fever, Tick, Simulation

INTRODUCTION

Crimean-Congo Hemorrhagic Fever (CCHF) is a zoonotic infection caused by Nairovirus that poses a serious threat to emergency healthcare systems, with mortality rates ranging from 3% to 30% and the potential to rapidly progress to disseminated intravascular coagulation and multiorgan failure (Aydın et al., 2026). The broad clinical spectrum of the disease and its potential progression to the hemorrhagic phase require emergency nurses to support their competencies in early diagnosis and case management with evidence-based strategies (Sarıkaya & Karaşahin, 2023). In particular, the management of thrombocytopenia, which occurs in 95%–100% of cases during the disease, and during of bleeding are critical determinants of the quality of nursing care (Binay & Özakgül, 2022). Moreover, the risk of transmission and the high mortality associated with the infection require nurses to move beyond standard protocols in their clinical decision-making and adopt preventive and therapeutic approaches consistent with the most current literature. (Akça et al., 2013; Tekin & Engın, 2020, p. 2) Although emergency nurses are reported to have high levels of knowledge, their attitudes toward caring for patients are often characterized by apprehension (Karamanlı & Dayapoğlu, 2021). Therefore, establishing disciplined use of personal protective equipment (PPE) to minimize the risk of nosocomial transmission and optimizing clinical practice standards on the basis of current evidence are essential for both patient health and healthcare worker safety (Karadakovan, 2010; Yolcu, 2014).

Eliminating uncertainties in case management may also increase nurses' professional self-confidence and help reduce reluctance to provide care in endemic areas (Akça et al., 2014).

In addition, the use of evidence-based diagnostic criteria incorporating laboratory parameters such as thrombocytopenia and changes in liver enzymes in the early diagnosis of patients presenting with atypical symptoms in emergency departments can reduce inappropriate triage and facilitate effective resource management. (Eren et al., 2010) In this context, the use of objective risk-scoring systems such as the Hitit Index may improve sensitivity and specificity in differentiating suspected cases presenting to emergency departments and thereby optimize diagnostic accuracy (Komut et al., 2023). Integrating laboratory findings into algorithms used in emergency department triage may also improve the rapid identification of disease burden and cases requiring hospitalization, particularly in endemic regions (Komut et al., 2022, p. 1; Yavuz & Yavuz, 2023). Furthermore, adoption of structured nursing frameworks in clinical decision-making can increase nurses' confidence in dealing with uncertainty and strengthen adherence to infection-control protocols (Alahmedi & Alodhialah, 2025; Oh & Jung, 2024). Awareness of the cognitive factors and clinical experiences that influence nurses' triage decisions for patients presenting with infectious diseases is essential for minimizing potential errors (Sun, 2026). Although the uncertainties encountered in emergency departments require nurses to adapt rapidly to changing case profiles, systematic clinical assessment and integration of current guidelines into practice constitute fundamental components of high-quality care (Lam et al., 2020). Accordingly, adoption of evidence-based guidelines in emergency nursing practice not only improves patient-centered outcomes but also strengthens healthcare workers' perceptions of safety and professional competence when managing high-risk infectious diseases (Alrfooh & Eladjaoui, 2026; Kim et al., 2022). Ensuring consistency between infection-management guidelines and daily practice is therefore critical for improving emergency nurses' case-management strategies (Lam et al., 2016). In addition, overcoming barriers such as inadequate infection-control measures and insufficient PPE use requires institutional

pandemic-safety strategies and training needs to be structured in accordance with current evidence in order to improve nurse safety and quality of care (Khraisat & Al-Bashaireh, 2024). In particular, systematic screening tools applied during triage are a key component supporting nurses' decision-making in the early detection of infection risk and rapid referral of patients to appropriate isolation areas. (Han & Yi, 2024; Laksmi et al., 2023) This approach can reduce inconsistencies in nurses' case-management practices and establish a standardized safety culture that limits the spread of infection (Ohunyon et al., 2020). To achieve this goal, it is essential to develop tailored training programs that enable emergency nurses to adapt rapidly to changing epidemiological conditions and strengthen their clinical decision-making skills (Lam et al., 2019). Indeed, incorporating evidence-based care protocols into routine workflows is necessary to address knowledge gaps and practice errors and to improve nurses' decision-making during crises (Yaman et al., 2022). In this context, implementation of evidence-based practice in emergency nursing not only improves patient outcomes but also enables nurses to use the specialized skills required in critical situations and make rational clinical decisions. This approach allows clinical expertise and scientific evidence to be integrated into a systematic decision-making mechanism (Öner & Öztürk, 2026). Such a systematic approach plays a strategic role in reducing uncertainties in care processes and improving nurses' clinical self-efficacy and quality of patient care, particularly under the heavy workload and limited resources of emergency departments (Lam et al., 2019; Kourakos & Kafkia, 2018). These competencies in clinical decision-making are directly associated with nurses' perceptions of professional self-efficacy and represent a major determinant of the accuracy of decisions made during crises. (Pillajo et al., 2024; Yücel et al., 2026)

Accordingly, integrating educational strategies and in-service practices aimed at strengthening clinical decision-making skills into an evidence-based nursing culture supports nurses in gaining autonomy and assuming more competent roles in care processes. (Baran et al., 2020, p. 353; ŞEN & Yurt, 2021, p. 103)

Particularly in diseases such as CCHF, which have a high mortality rate and a rapid clinical course, adoption of up-to-date evidence-based protocols by emergency nurses represents one of the strongest lines of defense for improving patient prognosis while minimizing occupational exposure (Menekli & Korkmaz, 2021). Evidence-based practices are a critical tool for reducing variability in clinical decisions and standardizing patient safety and quality of care. (Çelik et al., 2021; Çopur et al., 2015) Combining research findings with professional experience in clinical decision-making enables nurses to address complex health problems in a more systematic and analytical manner (Saharuddin et al., 2025). This holistic approach helps nurses standardize the quality of care, minimize the likelihood of medical errors, and improve patient satisfaction. (Yanmiş & Özcan, 2022). Adoption of evidence-based nursing practice as a professional standard also improves nurses' ability to identify and resolve complex clinical problems in light of the most current literature, producing tangible improvements in care outcomes. (Çor & İlçe, 2023; Yanıkkerem et al., 2023). In this context, integrating evidence-based nursing approaches into routine practice for conditions requiring emergency intervention, such as CCHF, can improve the quality of nursing care while contributing to cost-effective and safe healthcare delivery. (Kocaaslan et al., 2022) (Küçük et al., 2017). The use of evidence-based guidelines supports nurses in making autonomous decisions and strengthens their sense of professional responsibility and accountability (Aygün & Yıldırım, 2021). In addition, establishing a rational foundation based on scientific evidence in clinical decision-making increases nurses' professional self-efficacy in managing uncertainty in emergency department settings (Mumin & Nicole, 2024; Yücel et al., 2024). Thus, transferring the most current scientific findings into practice by integrating them with clinical experience can reduce errors arising in the management of complex cases and directly improve the safety and quality of healthcare services. (Nibbelink & Brewer, 2017; Serin et al., 2020) In high-risk situations requiring emergency intervention, such as the management of CCHF cases, evidence-based nursing practices improve clinical outcomes while minimizing healthcare personnel's exposure risk and contributing to a safe working environment (Ong & Toh, 2025; Yoo, 2025). Adoption of evidence-based methods also enables nurses to remain sensitive to patient values while providing care, close the gap between research and practice, and raise professional standards (Ovayolu et al., 2009). Evidence-based nursing management supports nurses' managerial decision-making capacity during rapidly progressing infectious processes such as CCHF and reduces safety vulnerabilities in the work environment (Üner & Baykal, 2024). Consequently, care processes shaped by continuously updated scientific evidence strengthen nurses' clinical expertise and standardize the delivery of individualized, high-quality healthcare. In this context,

nurses' regular monitoring of current research findings and integration of these data into patient-care processes are critical for maintaining professional standards and improving quality of care and clinical efficiency (Baltaci & Metin, 2021; Can & Özdemir, 2023). Therefore, grounding nursing services in scientific evidence supports standardization of care, minimization of practice errors, and adoption of an outcome-oriented professional approach. (Gedük, 2018).

LITERATURE REVIEW

In the literature, transforming nursing practices into evidence-based practice is considered essential for improving quality of care, making a difference in patient outcomes, and increasing professional satisfaction (Merih et al., 2017). Nurses' development of professional competence and effective translation of evidence-based practice procedures into clinical settings are fundamental determinants of sustaining quality standards in healthcare delivery. (Şahin & Çelik, 2025) Moreover, positive attitudes toward evidence-based practice among nurses create a strong expectation that these processes will be implemented more intensively and consciously in clinical settings. (Evcimen & Ayyildiz, 2019; Köse et al., 2023)

However, recent studies indicate that there are still implementation difficulties in translating complex interventions and developed protocols into clinical practice. In (Akçoban, 2023) particular, the gap encountered when transferring data obtained from clinical research into routine care processes reveals an important discrepancy between nurses' academic competencies and their practice in clinical settings (Akçoban, 2023). Indeed, these difficulties in integrating clinical experience with scientific evidence highlight the need for systematic strategies to guide nurses' decision-making processes. (Danski et al., 2017; Özpancar, 2016). In this context, current literature on the clinical course and transmission dynamics of CCHF demonstrates the vital role of standardized protocols in emergency nursing care. (Eren et al., 2015) understanding the transmission routes and disease stages of the virus carried by Hyalomma ticks and belonging to the Bunyaviridae family from a multidisciplinary perspective requires nurses to develop a proactive strategy for infection control. The occurrence of hematological findings, particularly thrombocytopenia and leukopenia, in the early stage of the disease makes rapid clinical decision-making competence vital for emergency nurses during case identification and isolation (AL-Salih et al., 2025). Considering the mortality rate of 10%–40%, improving nurses' knowledge during clinical processes plays a critical role in early diagnosis and implementation of effective isolation measures (Jasim & Ali, 2024). Nevertheless, studies show that although nurses may have high general knowledge about the disease, they have knowledge gaps in specific clinical areas such as treatment processes and laboratory findings (Karamanlı & Dayapoğlu, 2021). Although awareness of tick attachment and disease symptoms appears adequate among healthcare professionals, particularly those working in rural areas, the need for standardized training in specific medical interventions and prevention protocols remains (Aydın & Dumanlı, 2017). Accordingly, emergency nurses' clinical knowledge of CCHF should be continuously updated, and professional training programs should be standardized with a focus on the transmission routes of the disease and effective preventive measures. In clinical practice, the risk of contact with infected blood and body fluids, particularly those associated with Hyalomma ticks as vectors, requires nurses to apply isolation precautions meticulously. (Aydin & Dumanlı, 2017; Kazan & Sümer, 2019; Kamacı et al., 2024; Şahin, 2018). In this context, in addition to standard precautions, disciplined implementation of droplet and contact precautions during the care of infected patients is vital for minimizing occupational exposure among healthcare workers (Öngürü & Bodur, 2013). Accordingly, particularly in the management of cases encountered in endemic regions, PPE use and waste-management procedures should be implemented without compromise in accordance with current guidelines issued by infection-control committees in order to eliminate transmission risks (Firat et al., 2023). During triage of patients suspected of having CCHF, careful monitoring of early symptoms such as fever and generalized body pain constitutes the first line of defense against potential nosocomial transmission. (Çiçek & Çelik, 2023). Emergency nurses should obtain a detailed epidemiological history, rapidly identify individuals in high-risk groups, and activate infection-control protocols. (Günay et al., 2015; Sadettin, 2025). In addition, training interventions should strengthen nurses' risk perception and improve adherence to PPE use in order to reduce occupational exposure among healthcare personnel (Tümtürk, 2019).

Systematic training programs aimed at addressing gaps in healthcare professionals' knowledge positively affect nurses' attitudes toward protective practices, particularly in intensive care and

emergency department settings where the risk of nosocomial transmission is high (Ahmed et al., 2021). In this context, periodic training covering a broad range of topics, from PPE use to environmental disinfection, is a key strategy for minimizing the risk of nosocomial transmission in healthcare facilities. (Fletcher et al., 2017, p. 2) It should be remembered that direct contact with patients' secretions and contaminated body fluids substantially increases the risk of transmission to healthcare personnel (Kara, 2008).

Therefore, hands-on training on the correct donning and doffing of PPE plays a critical role in improving healthcare workers' adherence to infection-control procedures and their self-confidence (Gomez et al., 2025; Rebmann & Carrico, 2017). Such training interventions conducted in emergency departments have also been shown to produce statistically significant increases in nurses' knowledge scores and improve the quality of clinical practice (Atiyah & AliHattab, 2025). Furthermore, systematic implementation of clinical simulations and case-based training for all emergency department personnel can directly support outbreak preparedness and healthcare worker safety by removing barriers to transferring theoretical knowledge into practice (Jothishanmugam et al., 2025). The effectiveness of infection-control protocols in emergency departments is directly related not only to individual adherence but also to the establishment of continuous institutional monitoring and feedback mechanisms (Chiarella et al., 2016). The literature emphasizes that previous participation in training activities and awareness of PPE use are among the most important factors determining emergency workers' adherence to isolation precautions (Khudhur & Abdul-Wahhab, 2024; Kong et al., 2016). Nevertheless, discrepancies may sometimes be observed between nurses' self-reported infection-control behaviors and their actual clinical practices. These discrepancies have been attributed not only to attitudes toward infection control but also to variables such as organizational structure and workload (Choi & Park, 2025). Particularly in emergency departments characterized by high patient volume and limited resources, internal communication channels should be strengthened and continuous monitoring and feedback loops regarding PPE use should be established to ensure consistent implementation of isolation procedures (Yi & Cha, 2021). In addition, healthcare workers' knowledge of isolation precautions falling below a standard threshold is an important factor that may increase infection risk (Çelik et al., 2026; Sertçelik et al., 2023). Given that environmental barriers such as time constraints and high patient turnover reduce adherence to infection-control measures, practical simulation-based training that minimizes practice errors should be prioritized (Ellis, 2012; Liang et al., 2014). Simulation-based practices have demonstrated effectiveness in improving decision-making under high stress, translating theoretical knowledge into practical skills, and creating safe working environments. (Alzahrani et al., 2025; Jonson et al., 2017). The literature also supports that experience and regular training in infectious-disease management directly increase emergency departments' preparedness capacity and nurses' professional self-confidence. (Alzahrani et al., 2025; Laksmi et al., 2023). Furthermore, a positive organizational culture toward infection control is among the key determinants that strengthen nurses' adherence to isolation precautions and increase their perception of self-efficacy (Kim & Park, 2017). Given that greater professional experience and educational attainment are associated with better adherence to isolation procedures, continuity of institutional training programs plays a critical role in preventing the spread of infection (Özden & Özveren, 2016). Full compliance with infection-control standards is therefore regarded as an indispensable strategy for improving patient outcomes and ensuring healthcare worker safety (Alraimi & Alfadhli, 2023). Accordingly, infection-management strategies implemented in emergency departments should aim to establish a safe clinical environment by minimizing practice errors through a holistic approach supported by both updated theoretical knowledge and simulation-based practical training (Azab et al., 2023; Jin & Lee, 2020). In this context, simulation training that develops case-management skills for highly transmissible infections has been observed to substantially reduce error rates in emergency departments by improving nurses' clinical competence (Kim et al., 2024; Meagher et al., 2022). Moreover, these practical training interventions aimed at improving infection-control processes in healthcare facilities have been reported to strengthen emergency personnel's perception of exposure risk and their attitudes toward appropriate PPE use (Akça et al., 2013; Willet et al., 2026).

Simulation-based training in the management of high-risk pathogens also supports stress management during nurses' clinical decision-making and reinforces the overall safety culture in emergency departments. (Doğu & Bozkurt, 2024; Hunt et al., 2023). Practical experiences supported by simulation training further increase nurses' self-efficacy in stressful clinical scenarios such as infectious diseases

and minimize anxiety during the management of real cases (Blixt et al., 2022; Karataş & Tüzer, 2020). Periodic assessment of emergency nurses' current attitudes toward PPE use in endemic diseases such as CCHF is therefore critical for identifying and addressing potential gaps in adherence. (Yolcu, 2014) Such assessments increase nurses' participation in infection-control programs and significantly improve their professional knowledge and practical skills (Cha & Kee-Lyong, 2023; Park, 2026). Given the hematogenous and contact transmission risks associated with CCHF, periodically reinforcing emergency nurses' competence in case identification and implementation of isolation protocols through up-to-date simulation experiences plays a vital role in breaking the chain of infection within healthcare institutions (Abdelhady et al., 2026; Manuel et al., 2014). In this context, simulation-based practices that go beyond routine training improve nurses' knowledge and clinical performance in emergency management in a tangible manner and contribute to patient safety. (Lee & Ahn, 2019, p. 332; Rohachevskyi et al., 2025) Transfer of skills acquired through simulation training to clinical practice increases professionals' technical competence while optimizing their response capacity during outbreaks (Corvetto et al., 2023; Omer et al., 2026).

DISCUSSION

Management of CCHF cases in emergency departments is a complex process requiring continuity of nursing care and high adherence to infection-control protocols. In this pro (Khraisat & Al-Bashaireh, 2024) integrating simulation-based training into the curriculum beyond traditional methods to improve nurses' clinical competence plays a critical role in reducing error rates in emergency departments and establishing safe working environments. However, to ensure the (Savaş et al., 2025; Yi-Chen et al., 2025) sustainability of the effectiveness of simulation-based approaches, it is necessary to develop objective and validated assessment tools that measure the transfer of these competencies to real clinical settings rather than limiting evaluation to the training phase (Ju et al., 2025; Nikitara et al., 2025). In addition, structuring simulation-based scenarios to reflect the diversity and uncertainty of cases encountered in strengthens nurses' crisis decision-making processes and interprofessional coordination (Ghahremani et al., 2022; Lam et al., 2019). These practical experiences provided by simulation also reinforce competencies beyond technical skills, such as clinical reasoning and stress tolerance during crises, thereby increasing professional preparedness (Cho, 2024). Nevertheless, more comprehensive studies involving control groups are needed to verify the long-term clinical outcomes and retention of knowledge associated with simulation-based training and to further develop current practices (Chow et al., 2023). Training models supported by institutional mentoring programs and guided reflection processes can also increase nurses' self-confidence in clinical practice and contribute holistically to their professional development (Altınbaş et al., 2025; Pereira, 2025). Particularly in the management of high-risk pathogens, aligning simulation-based teaching strategies with clinical practice requirements is a fundamental strategy for closing the gap between theoretical knowledge and practical skills (Bliss & Aitken, 2017; Daneshfar & Moonaghi, 2025). Moreover, positioning advanced simulation strategies that require institutional investment not only as educational tools but also as patient-safety interventions that minimize errors can further enhance operational preparedness in emergency departments. Although the (Silva et al., 2026) success of simulation-based learning in nursing education is well documented in the literature, the limited evidence regarding the persistence of clinical competencies over time necessitates monitoring the long-term effects of these practices (Alharbi et al., 2024).

In this context, investigating the long-term effects of simulation-based training on clinical judgment, patient safety, and professional preparedness will provide critical evidence for restructuring nursing curricula through a competency-based approach. (Ntumi, 2025). Examining the extent to which learning outcomes from simulation-based training are effective, particularly in nurses' adaptation to high-intensity working conditions in emergency departments, is important for increasing their readiness for clinical practice (Kingston et al., 2025). In addition, minimizing the time during which students and clinical nurses remain in observer roles and maximizing active participation during simulation processes will strengthen the retention and transferability of learning outcomes to clinical settings. (Kelly et al., 2016, p. 330) Regular performance assessments and structured feedback processes for emergency nurses involved in the management of high-risk infectious diseases can support the transformation of theoretical knowledge into real clinical practice and optimize service quality. (Guerrero et al., 2024; Jarelnape & Sagiron, 2023) In-depth research on the transfer of competencies acquired after simulation training to clinical settings will guide the development of strategies that strengthen nurses' professional

roles (Andersson et al., 2023). In particular, the effects of high-fidelity simulation on nurses' ability to collaborate with multidisciplinary teams and make decisions under stress should be a focus of future research. Monitoring the long-term effects of such educational models on emergency nurses' clinical performance and the temporal retention of knowledge is also strategically important for updating nursing curricula. Consequently, simulation (Liaw et al., 2014) based approaches implemented in emergency departments should be expanded beyond technical skills to support multidimensional clinical judgment and crisis-management capacity, thereby making success in infection-control processes sustainable. Longitudinal (Song & Jeong, 2015) studies examining the role of simulation programs developed specifically for infectious diseases in improving nurses' psychological resilience during crises and the quality of patient care will contribute to the standardization of clinical practice. Parti (Ko & Choi, 2024, p. 237) in dynamic areas such as infection management, integration of virtual reality and advanced simulation modules may directly improve patient-care outcomes by increasing nurses' emergency preparedness and clinical competence (Hwang & Lee, 2021; Liaw et al., 2015). In addition, optimizing interprofessional communication methods in scenarios characterized by high uncertainty, such as disaster management and exposure to high-risk pathogens, represents a critical area for improving nurses' intervention effectiveness and team coordination (Ponce-Rivera et al., 2024). The use of standardized case scenarios involving multidisciplinary teams and validated measurement tools will allow more precise evaluation of the effects of emergency nursing practices on both patient-safety outcomes and professional competence. Such systematic evaluation processes can support the effectiveness of educational interventions with evidence-based data and enable continuous quality-improvement cycles in nursing practice (Lewis et al., 2019).Increasing the diversity of scenarios in simulation-based training also plays a key role in strengthening nurses' reflective thinking skills and capacity for emotional care when dealing with complex clinical situations (Leppänen et al., 2018). Particularly in conditions such as CCHF, where isolation protocols and rapid intervention are vital, simulation-based reflective practices directly support nurses' clinical reasoning and safety (Jang & Park, 2021).Integrating these clinical simulations with institutional mentoring systems will further strengthen professional support mechanisms by reinforcing the self-efficacy of nurses, particularly inexperienced nurses, in implementing infection-control protocols (Bias et al., 2016; O'Rourke et al., 2021). In this context, (Öner et al., 2025) integration of high-fidelity simulation into clinical practice should be considered a strategic approach for improving nurses' cognitive flexibility during emergencies and their coordination skills within multidisciplinary teams (Zhao et al., 2024).

CONCLUSION

Management of high-risk conditions such as CCHF requires continuous updating of evidence-based nursing practices and their support through systematic training programs. In future nursing practice, expanding longitudinal research that monitors the effects of simulation training on clinical outcomes is a critical requirement for achieving standardization in infection control. In addition, systematic use of checklists in emergency departments should be regarded as a fundamental tool for increasing consistency in nursing practice and optimizing both patient safety and protection of healthcare workers against infection risk. Accordingly, evidence-based guidelines integrated into institutional policy-development processes should become an indispensable component that enhances nurses' clinical competence and supports professional sustainability. Integrating such innovative approaches into nursing curricula and continuing education programs will reduce variation in clinical practice and facilitate the establishment of high-quality and safe standards of care across the healthcare system. This holistic approach will enable nurses to transfer evidence-based competencies acquired through innovative educational methods into clinical practice and build a sustainable safety culture in infection-management processes. Coordinating continuing professional development models with institutional policies will minimize variation in clinical practice and accelerate progress toward global standards in nursing care. Encouraging specialty-based postgraduate education and strengthening clinical mentoring systems will directly support the dissemination and sustainability of evidence-based practices in clinical settings. In this context, active participation of hospital management in research processes and establishment of evidence-based practice committees constitute critical steps toward institutionalizing quality of care and maximizing staff safety. Structural arrangements aimed at closing the gap between knowledge and practice will facilitate seamless transfer of evidence-based nursing practices from education to clinical settings and will be decisive in improving patient outcomes. Ultimately, integrating

scientific data with clinical expertise and patient needs will place the safety of care on a systematic foundation in complex clinical conditions such as CCHF. Encouraging healthcare professionals to engage in research in order to develop evidence-based attitudes and minimizing barriers in clinical practice constitute the basis of successful infection management. In addition, developing collaborative models between academic and clinical nurses will facilitate direct integration of evidence-based practice outcomes into clinical settings and strengthen nurses' professional competence and job satisfaction. Future research should focus particularly on the effects of digital health technologies and artificial intelligence-supported decision-support systems on infection surveillance processes in emergency departments, as this area has substantial potential to advance digital transformation and safety standards in nursing care. Moreover, establishing clinical audit mechanisms and regular feedback processes is vital for monitoring the effectiveness of guidelines in practice and proactively managing potential implementation errors. In this context, institutionalization of evidence-based leadership approaches will ensure that scientific evidence remains central to clinical decision-making, thereby systematically strengthening healthcare quality and patient safety.

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THE FOUNTAIN OF LIFE (ÇEŞME-İ HAYVÂN) IN KAYGUSUZ ABDÂL'S DÎVÂN: LIFE, BEAUTY, AND TRUTH

KAYGUSUZ ABDÂL DÎVÂNI'NDA ÇEŞME-İ HAYVÂN: HAYAT, GÜZELLİK VE HAKİKAT

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Abstract
The concept of çeşme-i hayvân ("the Fountain of Life") in the Dîvân of Kaygusuz Abdâl, who lived between the late fourteenth and early fifteenth centuries and is regarded as one of the founders of Alevi-Bektashi literature, is employed within various semantic relationships in addition to its traditional meanings and associations. In Classical Turkish literature and Sufi thought, çeşme-i hayvân is a symbolic concept associated not only with life-giving water and the source of immortality but also with such notions as truth and spiritual rebirth. This study examines the four couplets in Kaygusuz Abdâl's Dîvân in which the concept of çeşme-i hayvân appears and evaluates its meanings and functions within the poetic context. The aim of the study is to reveal the semantic relationships through which the concept of çeşme-i hayvân is used in Kaygusuz Abdâl's poetic world and to assess the dimensions of meaning it acquires through these usages. Using a text-centered method of analysis and interpretation, the study considers the relevant couplets within their respective contexts. The findings indicate that the concept is primarily associated with the beloved's lips and beauty and is subsequently presented as a source that grants life to the lover. In the instance where the poet identifies himself with the çeşme-i hayvân, the concept appears to be linked to human existence and spiritual truth. This usage also allows the concept to be evaluated in terms of spiritual guidance and its function of leading one to the truth. Furthermore, the assertion that the çeşme-i hayvân should be sought within one's own çeşm (eye/inner perception), the association of cehl (ignorance) with zulmet (darkness), demonstrate that the concept is connected with human cognition and the quest for truth. Consequently, it may be concluded that in Kaygusuz Abdâl's poetry the çeşme-i hayvân acquires a multidimensional semantic structure extending from beauty and love to the inner world of the human being and ultimately to the search for truth and understanding. In this respect, while preserving its traditional associations with life and immortality, the çeşme-i hayvân emerges as a Sufi image that is reinterpreted in relation to the beloved, the lover, and the human being.
Keywords: Kaygusuz Abdâl, Dîvân, Fountain of Life (Çeşme-i Hayvân), Sufism, Beauty, Truth.

Özet
14. yüzyılın sonu ile 15. yüzyılın başlarında yaşamış ve Alevi-Bektaşi edebiyatının kurucusu kabul edilen Kaygusuz Abdâl'ın *Dîvân*'ında "çeşme-i hayvân" kavramı, geleneksel anlam ve çağrışımlarının yanı sıra farklı anlam ilişkileri içerisinde kullanılmaktadır. Klasik Türk edebiyatında ve tasavvufî düşüncede "çeşme-i hayvân", hayat veren su ve ölümsüzlük kaynağı anlamlarının yanı sıra hakikat ve manevî diriliş gibi anlamlarla ilişkilendirilen sembolik bir kavramdır. Bu çalışmada, *Kaygusuz Abdâl Dîvânı*'nda "çeşme-i hayvân" kavramının geçtiği dört beyit incelenerek kavramın şiir içerisindeki anlam ve işlevleri değerlendirilecektir. Çalışmanın amacı, "çeşme-i hayvân" kavramının Kaygusuz Abdâl'ın şiir dünyasında hangi anlam ilişkileri içerisinde kullanıldığını ortaya koymak ve bu kullanımlar aracılığıyla kavramın kazandığı anlam boyutlarını değerlendirmektir. Araştırmada metin merkezli çözümleme ve yorumlama yöntemi kullanılarak "çeşme-i hayvân" kavramının geçtiği beyitler bağlamları içerisinde ele alınmıştır. İnceleme sonucunda kavramın öncelikle sevgilinin dudağı ve güzelliğiyle ilişkilendirildiği, ardından âşığa hayat veren bir kaynak olarak ele alındığı görülmektedir. Şairin kendisini "çeşme-i hayvân" ile özdeşleştirdiği kullanımda ise kavramın insan varlığı ve manevi hakikatle ilişkilendirildiği anlaşılmaktadır. Bu kullanım "çeşme-i hayvân"ın manevi rehberlik ve hakikate ulaştırma işlevleri açısından değerlendirilmesine de imkân vermektedir. Ayrıca "çeşme-i hayvân"ın insanın kendi "çeşm"inde aranması gerektiğinin belirtilmesi ve cehl kavramının zulmet ile ilişkilendirilmesi, kavramın insanın idrak alanı ve hakikat arayışıyla ilişkilendirildiğini göstermektedir. Böylece Kaygusuz Abdâl'ın şiirlerinde "çeşme-i hayvân"ın güzellik ve aşktan insanın iç dünyasına,

oradan da hakikat ve idrak arayışına uzanan çok boyutlu bir anlam yapısı kazandığı sonucuna ulaşılmıştır. Bu yönüyle "çeşme-i hayvân", geleneksel hayat ve ölümsüzlük çağrışımlarını korurken sevgili, âşık ve insan bağlamlarında yeniden anlamlandırılan tasavvufî bir imge olarak öne çıkmaktadır.
Anahtar Kelimeler: Kaygusuz Abdâl, Dîvân, Çeşme-i Hayvân, Tasavvuf, Güzellik, Hakikat.

FROM THE INDIVIDUAL TO SOCIAL STRUCTURE: THE HISTORICAL AND CONCEPTUAL TRANSFORMATION OF THEORIES OF CRIME

BİREYDEN TOPLUMSAL YAPIYA: SUÇ TEORİLERİNİN TARİHSEL VE KAVRAMSAL DÖNÜŞÜMÜ

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Abstract
The causes of crime have been explained at different levels since the emergence of criminology. Biological theories have focused on offenders' physical and hereditary characteristics, psychological theories on personality and mental processes, and sociological theories on the social conditions in which crime occurs. This study compares the historical development of biological, psychological, and sociological theories of crime. As a conceptual review, it evaluates classical and contemporary literature according to the theories' units of analysis, conceptions of causality, and approaches to the relationship between the individual and the social environment. Early positivist explanations largely associated crime with offenders inherited or acquired characteristics. With the development of psychological approaches, personality, cognition, learning, and childhood experiences gained prominence. Sociological theories shifted attention toward social environment, social structure, inequality, culture, and processes of social control. These theoretical differences also influenced how crime was defined and which forms of intervention were favored. Biological and psychological explanations generally emphasized offender assessment and individual intervention, whereas sociological approaches placed greater weight on changing social conditions and criminogenic environments. Biological and psychological perspectives continued to develop and were reconsidered in light of new scientific findings. Biosocial criminology, developmental criminology, life-course perspectives, and integrated theories are the principal contemporary examples of this transformation. The historical development of theories of crime has broadened the focus of inquiry from offenders' biological and psychological characteristics to their social environments and structural conditions. This theoretical change has shaped both knowledge about the causes of crime and policies concerning prevention and offender rehabilitation. The combined use of different perspectives now offers a more comprehensive account of the multidimensional nature of criminal behavior. Understanding the causes of crime therefore requires offenders' characteristics, life experiences, immediate environments, and wider social structures to be considered together.
Keywords: Theories of crime, biological theories, psychological theories, sociological theories, integrated theories.

Özet
Suçun nedenleri, kriminolojinin kuruluşundan bu yana farklı düzeylerde açıklanmıştır. Biyolojik teoriler failin bedensel ve kalıtsal özelliklerine, psikolojik teoriler kişilik yapısına ve zihinsel süreçlere, sosyolojik teoriler ise suçun ortaya çıktığı toplumsal koşullara odaklanmıştır. Bu çalışma, biyolojik, psikolojik ve sosyolojik suç teorilerinin tarihsel gelişimini ve kriminolojik düşünceye sağladıkları katkıları karşılaştırmalı olarak incelemeyi amaçlamaktadır. Kavramsal bir derleme olarak tasarlanan çalışmada klasik ve çağdaş kriminoloji literatürü, teorilerin analiz birimleri, suça ilişkin nedensellik anlayışları ve birey ile toplumsal çevre arasında kurdukları ilişkiler üzerinden değerlendirilmiştir. Erken dönem pozitivist açıklamalar suçu büyük ölçüde failin doğuştan gelen veya sonradan kazandığı özelliklerle ilişkilendirmiştir. Psikolojik yaklaşımların gelişmesiyle kişilik, biliş, öğrenme ve çocukluk deneyimleri önem kazanmıştır. Sosyolojik teoriler ise araştırmanın yönünü bireyin içinde bulunduğu sosyal çevreye, toplumsal yapıya, eşitsizliğe, kültüre ve sosyal denetim süreçlerine çevirmiştir. Teoriler arasındaki farklılıklar, suçun nasıl tanımlandığını ve hangi müdahale araçlarının benimsendiğini de etkilemiştir. Biyolojik ve psikolojik açıklamalar daha çok failin değerlendirilmesine ve bireysel müdahalelere yönelirken, sosyolojik yaklaşımlar toplumsal koşulların ve suç üreten çevrelerin değiştirilmesine ağırlık vermiştir. Biyolojik ve psikolojik açıklamalar tarihsel süreç içinde varlığını sürdürmüş ve yeni bilimsel bulgular doğrultusunda yeniden ele alınmıştır. Biyososyal kriminoloji, gelişimsel kriminoloji, yaşam seyri yaklaşımı ve bütünleşik teoriler bu dönüşümün günümüzdeki başlıca örneklerini oluşturmaktadır. Bu yaklaşımlar aynı zamanda disiplinler arası araştırmaların gelişmesini

desteklemektedir. Suç teorilerinin tarihsel gelişimi, araştırmanın odağını failin biyolojik ve psikolojik özelliklerinden toplumsal çevreye ve yapısal koşullara doğru genişletmiştir. Bu kuramsal değişim, suçun nedenlerine ilişkin bilgi üretimini olduğu kadar suçun önlenmesi ve suçlunun yeniden topluma kazandırılması amacıyla geliştirilen politikaları da doğrudan etkilemiştir. Günümüzde farklı teorik yaklaşımların birlikte kullanılması, suç davranışının çok boyutlu yapısını anlamayı kolaylaştırmaktadır. Suçun nedenlerini anlamak için failin özelliklerinin, yaşam deneyimlerinin, yakın çevresinin ve içinde bulunduğu toplumsal yapının birlikte değerlendirilmesi gerekmektedir.
Anahtar kelimeler: Suç teorileri, biyolojik teoriler, psikolojik teoriler, sosyolojik teoriler, bütünleşik teoriler.

A PHILOSOPHICAL LOOK AT THE RELATIONSHIP BETWEEN EMOTIONS AND MORALITY WITHIN THE FAMILY

AİLENİN ZEMİNİNDEKİ DUYGULARLA AHLÂK ARASINDAKİ İLİŞKİYE FELSEFİ BİR BAKIŞ

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Abstract
Explanations of the continuity of the family tend to reduce it solely to biological ties, legal status, or social division of labor. It is therefore imperative to offer a philosophical assessment that also views the family institution as a moral unity founded on constitutive emotions such as love and respect. This paper specifically considers practical analyses of the distinction between respect and love found in Kantian thought. Along with the broader conceptual possibilities of the philosophy of emotion, the main relationships within the family are reconsidered and re-evaluated. Within this framework, emotions such as love, respect, affection, reverence, gratitude, and sympathy directed towards each other (spouses towards each other, parents towards children, children towards their parents, and family members towards their elders) are examined separately. The paper demonstrates that love is not merely a natural inclination or emotional closeness, but also carries a practical aspect aimed at the well-being of the other in specific relationships. It also argues that respect is not merely an attitude adopted to maintain distance, but a moral principle that recognizes the personality and dignity of the other. Kant emphasizes that even in duties related to love, the determining motive is the feeling of respect. Practical obligations such as benevolence, gratitude, sympathy, and mutual care are also within the framework of respect. Mutual love within the family is not merely an expression of emotional attachment. Accordingly, love as a moral duty should be considered a conscious inclination that protects the personalities of family members. Consequently, the statement interprets the family as a moral unity made possible through a balance established between the warmth of love and the limiting power of respect.
Keywords: Family, love, respect, morality, Kant

Özet
Ailenin sürekliliğine dair açıklamalar onu yalnızca biyolojik soy bağına, hukuki statüye ya da toplumsal iş paylaşımına indirgeme eğilimindedir. Aile kurumunu, aynı zamanda sevgi ve saygı gibi kurucu duygular üzerine kurulan ahlaki bir birlik olarak gören felsefi bir değerlendirme ortaya koymak da bu noktada bir zorunluluktur. Bildiride özellikle Kant düşüncesinde karşımıza çıkan saygı ve sevgi ayrımına ilişkin pratik çözümlemeler dikkate alınmaktadır. Duygu felsefesinin daha geniş kavramsal imkânlarıyla birlikte, aile içindeki başlıca ilişkiler yeniden düşünülüp değerlendirilmektedir. Bu çerçevede eşlerin birbirlerine, anne babanın çocuklarına, çocukların anne babalarına ve aile fertlerinin aile büyüklerine yönelttiği sevgi, saygı, şefkat, hürmet, minnettarlık ve sempati gibi duygular ayrı ayrı ele alınmaktadır. Bildiride sevginin yalnızca doğal bir eğilim veya duygusal bir yakınlık olmadığı, belirli ilişkilerde ötekinin iyiliğini amaç edinen pratik bir yön taşıdığı da ortaya konulmaktadır. Saygı duygusunun yalnızca mesafeleri korumak için ortaya konulan bir tutum olmadığı, ötekinin kişiliğini ve onurunu tanıyan ahlaki bir ilke olduğu da savunulmaktadır. Kant'ın vurgusu, sevgiyle ilgili ödevlerde bile belirleyici güdünün saygı duygusunun olduğu yönündedir. İyilikseverlik, minnettarlık, sempati ve karşılıklı gözetim gibi pratik yükümlülükler de saygı çerçevesinin içindedir. Ailede karşılıklı olarak duyulan sevgi, yalnızca duygusal bir bağlılığın ifadesi değildir. Buna göre ahlâkî bir ödev olarak sevginin, aile fertlerinin kişiliklerini koruyan bilinçli bir yöneliş olduğu kabul edilmelidir. Sonuç olarak bildiride aile, sevginin sıcaklığı ile saygının sınır koyucu gücü arasında kurulan denge yoluyla mümkün olan ahlaki bir birlik olarak yorumlanmaktadır.
Anahtar kelimeler: Aile, sevgi, saygı, ahlâk, Kant

AUDIENCE PERCEPTION OF AI-GENERATED ADVERTISEMENTS: THE CASE OF THE CEM YILMAZ GOFRİK COMMERCIAL

YAPAY ZEKA ÜRETİMİ REKLAMLARA YÖNELİK İZLEYİCİ ALGISI: CEM YILMAZ GOFRİK REKLAMI ÖRNEĞİ

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Abstract
The rapid development of artificial intelligence (AI) technologies is creating fundamental transformations in advertising design and marketing communication. To create remarkable atmospheres and reinforce positive consumer evaluations toward the advertisement and the brand, companies are increasingly resorting to AI-based visual production over traditional methods. This shift makes it important to examine the effects of technological aesthetics on audience perception. Consequently, this study aims to investigate the impact of AI use in advertising design on the audience's perception of realism and their brand evaluations. Accordingly, the Gofrik commercial, featuring Cem Yılmaz and depicting a dystopian Istanbul in 2100, was examined. Adopting a qualitative research design, semi-structured in-depth interviews were conducted with seven university students. Findings indicate that participants clearly noticed the AI-generated environments, such as the dried-up Bosphorus and ruined buildings. However, this dystopian atmosphere was not found repulsive. On the contrary, it was likened to blockbuster post-apocalyptic films and evaluated as an impressive, immersive, and engaging visual language. Most participants perceived the use of AI visuals not as a shortcut to cut advertising budgets, but as a necessary "technological and creative vision" for constructing a futuristic scenario. Furthermore, the inclusion of AI aesthetics did not negatively affect viewing pleasure or perspective toward the brand regarding ultimate purchase intention. Instead, participants stated that significant intellectual effort lies behind using innovative technologies in advertising, which they deemed valuable. They also evaluated the brand as contemporary, likable, and open to innovation. In conclusion, creatively constructed AI-supported advertising visuals do not evoke negative consumer reactions; rather, they enhance the aesthetic experience and build effective marketing communication without undermining positive brand evaluations.
Keywords: Advertising, Artificial Intelligence, Audience Perception, AI Advertising

Özet
Yapay zeka (YZ) teknolojilerindeki hızlı gelişim, reklam tasarımı ve pazarlama iletişiminde köklü dönüşümler yaratmaktadır. Markalar, dikkat çekici atmosferler oluşturmak ve tüketicilerin reklama ve markaya yönelik olumlu değerlendirmelerini pekiştirmek için geleneksel prodüksiyon yöntemleri yerine giderek artan bir şekilde YZ tabanlı görsel üretimine başvurmaktadır. Bu durum, teknolojik estetiğin izleyici algısı ve tüketicilerin duygusal eğilimleri üzerindeki etkilerini incelemeyi önemli kılmaktadır. Bu çalışmanın amacı, reklam tasarımında YZ kullanımının izleyicinin gerçekçilik algısına ve markaya yönelik değerlendirmelerine etkisini araştırmaktır. Bu doğrultuda, Cem Yılmaz'ın rol aldığı ve 2100 yılının distopik İstanbul'unu tasvir eden Gofrik reklamı incelenmiştir. Araştırmada nitel araştırma deseni benimsenerek, üniversite öğrencilerinden oluşan 7 katılımcıyla yarı yapılandırılmış derinlemesine görüşmeler gerçekleştirilmiştir. Elde edilen bulgulara göre, katılımcılar reklamdaki kurumuş İstanbul Boğazı ve harabe binalar gibi YZ üretimi mekanları açıkça fark etmiştir. Ancak bu distopik atmosfer izleyiciler tarafından itici bulunmamış; aksine gişe rekorları kıran popüler post-apokaliptik filmlere benzetilerek son derece etkileyici, sürükleyici ve ilgi çekici bir görsel dil olarak değerlendirilmiştir. Katılımcıların çoğunluğu, gerçek set yerine YZ görsellerine başvurulmasını basitçe emekten veya reklam bütçesinden kaçmak olarak değil, fütüristik senaryonun inşası için gereksinim duyulan "teknolojik ve yaratıcı bir vizyon" olarak algılamıştır. Ayrıca, reklamda YZ estetiğinin yer alması,

izleyicilerin reklamı izleme zevkini veya nihai satın alma niyeti bağlamında markaya yönelik bakış açısını olumsuz yönde etkilememiştir. Aksine, katılımcılar güncel ve yenilikçi teknolojilerin reklam evreninde kullanılmasının arkasında ciddi bir zihinsel çaba yattığını ve bunun kıymetli olduğunu ifade etmişlerdir. Bunun yanı sıra katılımcılar, markayı yeniliklere açık, çağdaş ve sempatik olarak değerlendirmişlerdir. Sonuç olarak, araştırma kapsamında yaratıcı bir şekilde kurgulanan yapay zeka destekli reklam görsellerinin, tüketicilerde olumsuz bir tepki uyandırmadığı, aksine estetik deneyimi güçlendirdiği ve markaya yönelik olumlu değerlendirmeleri zedelemeden oldukça etkili bir pazarlama iletişimi inşa ettiği düşünülmektedir.

Anahtar kelimeler: Reklam, Yapay Zeka, İzleyici Algısı, Yapay Zeka Reklamları

TÜRKİYE'DE DEZAVANTAJLI GRUPLARA YÖNELİK SOSYAL POLİTİKALAR VE MEKANA YANSIMALARI[1]

SOCIAL POLICIES FOR DISADVANTAGED GROUPS IN TÜRKİYE AND THEIR SPATIAL IMPLICATIONS[2]

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Özet
Dezavantajlılık, bireylerin ekonomik, sosyal ve fiziksel kaynaklara, hizmetlere ve fırsatlara erişimini sınırlandıran çok boyutlu bir durumdur. Dezavantajlılık konusunda en çok çalışılan ve öne çıkan gruplar kadınlar, çocuklar, engelliler, yaşlılar, yoksullar, göçmenler vb.'dir. Ülkelerin dezavantajlı gruplar için politika(lar)geliştirmesi ve bu politikalar için mekana yansıyacak uygulama araçları oluşturması bu grupların kentsel haklardan faydalanmaları için önemlidir.
Bu kapsamda çalışma, Türkiye'de dezavantajlı gruplara yönelik geliştirilen sosyal politikaları ve bu politikaların fiziksel mekândaki karşılıklarını incelemeyi amaçlamaktadır. Bu doğrultuda, sosyal politika üretimi ve uygulanmasında rol üstlenen kurumsal aktörlerden Aile ve Sosyal Hizmetler Bakanlığı ile Çevre, Şehircilik ve İklim Değişikliği Bakanlığı'nın dezavantajlı gruplara yönelik görev ve yetkileri, politika belgeleri ve ilgili mevzuatı değerlendirilmiştir. Araştırmada nitel araştırma yöntemlerinden içerik analizi kullanılmış; bakanlıkların kurumsal dokümanları, stratejik politika belgeleri, kanunlar, yönetmelikler ve yönergeler sistematik olarak incelenmiştir. İncelenen düzenlemelerde dezavantajlı gruplara yönelik hizmetlerin konut, sosyal tesis, bakım ve rehabilitasyon merkezleri, konukevleri, çocuk bakım kuruluşları ve erişilebilirlik düzenlemeleri gibi fiziksel ve mekânsal karşılıkları belirlenmiştir. Araştırma bulguları, dezavantajlı gruplara ilişkin üst ölçek politika belgelerinde ortaya konulan hedefler ile alt ölçek mevzuat ve uygulamalar arasında farklılıklar bulunduğunu göstermektedir. Özellikle iklim değişikliği ve afetlere karşı dirençlilik, kadınların ve çocukların korunması ile engelli bireylerin erişilebilirliği konularında üst ölçek politika belgelerinde kapsamlı hedefler tanımlanmasına karşın, bu hedeflerin bir bölümünün alt ölçek mevzuatta yeterli karşılık bulmadığı belirlenmiştir. Sonuç olarak çalışma, dezavantajlı gruplara yönelik sosyal politika hedeflerinin fiziksel mekâna etkili biçimde yansıtılabilmesi için üst ölçek politika belgeleri ile alt ölçek mevzuat ve uygulama araçları arasındaki ilişkinin güçlendirilmesi; dezavantajlı grupların erişilebilirlik, kullanılabilirlik ve mekânsal gereksinimlerinin planlama ve tasarım süreçlerine daha sistematik biçimde aktarılması gerektiğini ortaya koymaktadır.
Anahtar Kelimeler: Dezavantajlı Gruplar, Şehir Planlama, Sosyal Politika, Mekân, Erişilebilirlik.

Abstract
Disadvantage is a multidimensional condition that constrains individuals' access to economic, social, and physical resources, services, and opportunities. Among the groups most frequently addressed in

[1] Bu çalışma Dokuz Eylül Üniversitesi Fen bilimleri Enstitüsü Öğretim planında yer alan PLN 6020 Ötekiler ve Fiziksel Planlama dersi (Ders Koordinatörü Prof. Dr. Mercan EFE GÜNEY) kapsamında yapılan çalışmalardan geliştirilmiştir.
[2] This study was developed from work conducted within the scope of PLN 6020 *Others and Physical Planning*, a course included in the curriculum of the Graduate School of Natural and Applied Sciences at Dokuz Eylül University and coordinated by Prof. Dr. Mercan EFE GÜNEY.

research on disadvantage are women, children, persons with disabilities, older persons, low-income populations, and migrants. Developing policies for disadvantaged groups, along with implementation instruments that translate these policies into spatial interventions, is essential to enabling these groups to exercise their urban rights effectively.

Within this framework, this study aims to examine social policies developed for disadvantaged groups in Türkiye and assess their spatial manifestations in the physical environment. To this end, the mandates, responsibilities, policy documents, and relevant legislation of the Ministry of Family and Social Services and the Ministry of Environment, Urbanization and Climate Change—two key institutional actors in the formulation and implementation of social policies—are evaluated. The study employs qualitative content analysis and systematically examines institutional documents, strategic policy documents, laws, regulations, and directives issued by both ministries. The analysis identifies the physical and spatial manifestations of services targeting disadvantaged groups, including housing, social facilities, care and rehabilitation centers, shelters, childcare facilities, and accessibility arrangements. The findings reveal discrepancies between the objectives articulated in higher-level policy documents concerning disadvantaged groups and their incorporation into lower-level legislation and implementation practices. In particular, although higher-level policy documents establish comprehensive objectives concerning resilience to climate change and disasters, the protection of women and children, and accessibility for persons with disabilities, some are not adequately reflected in lower-level legislation. The study concludes that strengthening alignment between higher-level policy documents and lower-level legislation and implementation instruments is essential for effectively translating social policy objectives into the physical environment. Furthermore, the accessibility, usability, and spatial needs of disadvantaged groups should be systematically integrated into planning and design processes.

Keywords: Disadvantaged Groups, Urban Planning, Social Policy, Space, Accessibility.

PERSONIFICATIONS IN THE EARLY BYZANTINE PERIOD MOSAICS OF THE OLYMPOS ANCIENT CITY

OLYMPOS ANTİK KENTİ ERKEN BİZANS DÖNEMİ MOZAİKLERİNDE KİŞİLEŞTİRMELER

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Abstract
Located on the eastern coast of Lycia, Olympos stands out as one of the most important coastal settlements of antiquity owing to its natural harbor, topographical characteristics, and the regional role it played throughout its history. Archaeological and epigraphic evidence indicates that the city was an important settlement during the Hellenistic period and that, following the reign of Augustus, a rebuilding process began through which its Roman identity was redefined. The presence of numerous monumental religious structures dating to the 5th and 6th centuries AD also indicates that extensive building activity took place in the city during this period in connection with the spread of Christianity.
Archaeological excavations in the city have uncovered mosaics featuring personifications in the atrium of Church No. 3 and around the peristyle of the *Episkopeion*. In addition, a city personification is depicted in front of the northern entrance to the atrium of Church No. 1. The personifications are represented in bust form and are accompanied by inscriptions identifying them. The mosaics, executed in the *opus tessellatum* technique, are dated to the 6th century AD.
The peristyle is surrounded by porticoes on three sides and features a monumental fountain along its western wall. Given its architectural arrangement and location within the complex, the peristyle appears to have served functions associated with healing and the sacred use of water. The mosaics surrounding the peristyle include personifications identified by the inscriptions *ΚΤΗ/CIC* (ktesis – creation), *ΤΡΥ/ΦΗ* (tryphe – luxury), *ΧΑ/PIC* (kharis – grace), *ΑΠΟ/ΛΑΥCIC* (apolausis – pleasure), and *CO/ΦOC* (sophos – wisdom).
Church No. 3 is a three-aisled basilica. To the west of the church lies an atrium surrounded by porticoes on three sides. The western wall of the atrium is arranged as a fountain. The mosaics in the atrium depict personifications identified as *ΕΙΡΗΝΗ* (eirene – peace), *ΠΙΣΤΗΣ* (pistis – faith), *ΣΟΦΙΑ* (sophia – wisdom), *ΑΝΔΡΕΙΑ* (andreia – courage) and *ΔΙΚΑΙΟΣΥΝΗ* (dikaiosyne – justice).
This study presents detailed descriptions of these personifications and examines them in relation to their conceptual counterparts in Early Christian theology.
Keywords: Early Christianity, Byzantine Archaeology, Lycia, Mosaic, Personification

Özet
Lykia Bölgesi'nin doğu kıyısında yer alan Olympos, sahip olduğu doğal limanı, topoğrafik özellikleri ve tarih boyunca üstlendiği bölgesel rol sayesinde antik çağın önemli kıyı yerleşimlerinden biri olarak öne çıkmaktadır. Arkeolojik ve epigrafik veriler kentin Hellenistik dönemde önemli bir yerleşim olduğuna, Augustus dönemi sonrasında ise Romalı kimliği ile yeniden inşa sürecine başlandığına işaret eder. MS. 5. ve 6. yüzyıllara tarihlenen çok sayıda anıtsal dini yapının varlığı da kentte bu dönemde Hristiyanlıkla birlikte kapsamlı bir imar faaliyeti gerçekleştirildiğini gösterir.
Kentte sürdürülen arkeolojik kazı çalışmalarında 3 No'lu Kilise atriumunda ve *episkopeion* (piskoposluk sarayı) içerisindeki peristyl ve çevresinde kişileştirme tasvirleri içeren mozaikler açığa çıkarılmıştır. Ayrıca 1 No'lu Kilise'nin atrium kuzey giriş kapısı önünde de bir kent kişileştirmesi bulunur. Kadın büstü şeklinde tasvir edilen kişileştirmelerin başlarının iki yanında temsil ettikleri kavramları ya da kimliği ifade eden yazıtlarıyla birlikte gösterilmiştir. *Opus-tesselatum* tekniğindeki mozaikler MS 6. yüzyıla tarihlenmektedir.
Batı duvarında anıtsal bir çeşmeye sahip peristyl üç yönden portikolarla çevrilidir. Kompleks içindeki yerleşimi ve konumu nedeniyle, peristylin şifayla ve suyun kutsal kullanımıyla ilişkili bir işlevi olduğu anlaşılmaktadır. Peristyl çevresindeki mozaiklerde *KTH/CIC* (ktesis – yaratma), *TPY/ΦH* (tryphe – sefahat), *XA/PIC* (kharis – fazilet yada lütuf), *ΑΠΟ/ΛΑΥCIC* (apolausis – saadet) ve *CO/ΦOC (sophos – bilge kişi)* tasvirleri bulunur.

3 No'lu Kilise üç nefli bazilikal plan şemasındadır. Kilisenin batısında üç yönden portikolarla çevrili bir atrium bulunur. Atriumun batı duvarı çeşme olarak düzenlenmiştir. 3 No'lu Kilise'nin atrium mozaiklerinde *ΕΙΡΉΝΗ* (eirene – barış), *ΠΙΣΤΗΣ* (pistis – inanç), *ΣΟΦΊΑ* (sophia – bilgelik), *ἈΝΔΡΕΊΑ* (andreia – cesaret) ve *ΔΙΚΑΙΟΣΥΝΗ* (dikaiosyne – adalet) tasvirleri yer alır.
Bildiride kişileştirme tasvirleri detaylı olarak tanıtılacak ve Erken Hıristiyanlık dönemi teolojisindeki kavramsal karşılıklarıyla birlikte ele alınarak değerlendirilecektir.

Anahtar kelimeler: Erken Hıristiyanlık, Bizans Arkeolojisi, Lykia, Mozaik, Kişileştirme

EVALUATION OF PEDIATRIC OUTPATIENT CLINICS IN TERMS OF SPATIAL QUALITY AND USER EXPERIENCE: THE CASE OF DÜZCE

ÇOCUK POLİKLİNİKLERİNİN MEKÂNSAL KALİTE VE KULLANICI DENEYİMİ AÇISINDAN DEĞERLENDİRİLMESİ: DÜZCE ÖRNEĞİ

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Abstract
Healthcare facilities are complex spatial systems that directly influence users' physical and psychological well-being. In this context, the concept of healing environment design highlights the role of spatial quality in patients' physical and psychological recovery processes. In the design of healing environments for children, attention should be paid not only to general design principles but also to children's sensory and perceptual characteristics, as well as the comfort of accompanying caregivers and ease of wayfinding. Accordingly, accessibility, ease of wayfinding, environmental comfort, child-scaled and ergonomically appropriate furnishings, and the quality of waiting areas emerge as significant components in the evaluation of child-oriented healthcare environments. Although international literature has demonstrated that the relationship between spatial quality and user experience varies across institutional and cultural contexts, relatively few studies in Türkiye have comparatively examined this relationship specifically in pediatric outpatient clinics in public and private hospitals.
This study aims to comparatively evaluate the pediatric outpatient clinics of Düzce Atatürk State Hospital (public) and Düzce Private Çağsu Hospital (private), located in the medium-sized city of Düzce, in terms of spatial quality and user experience. The research is designed as a mixed-methods study integrating architectural documentation, on-site measurements, computer-based simulation, user surveys, and behavioral observation. Three-dimensional models of selected areas and examination rooms will be developed to analyze daylighting and visual comfort performance through simulations. Spatial organization and circulation characteristics will also be evaluated through plan-based analyses. The resulting objective data will be compared with users' assessments of spatial perception, comfort, and satisfaction to investigate the relationships between the physical environment and user experience. The study is expected to provide a methodological framework for evaluating spatial quality and user experience in pediatric outpatient clinics, contribute to the relevant literature, and support the development of assessment criteria for the design of child-oriented healthcare environments.
Keywords: Pediatric outpatient clinics, spatial quality, user experience, daylight simulation, child-oriented healthcare environments.

Özet
Sağlık yapıları, kullanıcıların fiziksel ve psikolojik iyilik hâllerini doğrudan etkileyen karmaşık mekânsal sistemlerdir. Bu bağlamda gelişen iyileştirici mekân tasarımı yaklaşımı, mekânsal kalitenin hastanın fiziksel ve psikolojik iyileşme sürecindeki rolünü ortaya koymaktadır. Çocuklara yönelik iyileştirici mekân tasarımlarında ise, genel ilkelerin yanı sıra çocukların duyusal ve algısal özelliklerinin de dikkate alınması, ayrıca refakatçilerin rahatlığı ve yön bulma kolaylığı gibi unsurların da önemsenmesi gerekmektedir. Bu bağlamda erişilebilirlik, yön bulma kolaylığı, çevresel konfor, çocuk ölçeğine ve ergonomisine uygun donatılar ve bekleme alanlarının niteliği, çocuk odaklı sağlık mekânlarının değerlendirilmesinde önem taşıyan bileşenler olarak öne çıkmaktadır. Uluslararası literatürde mekânsal kalite ile kullanıcı deneyimi arasındaki ilişkinin kurumsal ve kültürel bağlama göre farklılaştığı ortaya konmuş olsa da, Türkiye'de bu ilişkinin kamu ve özel hastanelerin çocuk poliklinikleri özelinde karşılaştırmalı olarak ele alındığı çalışmalara sınırlı sayıda rastlanmaktadır.
Bu çalışma, orta ölçekli bir şehir olan Düzce'de hizmet veren Düzce Atatürk Devlet Hastanesi (kamu) ve Düzce Özel Çağsu Hastanesi (özel) çocuk polikliniklerinin mekânsal kalite ve kullanıcı deneyimi açısından karşılaştırmalı olarak değerlendirilmesini amaçlamaktadır. Araştırma, mimari belgeleme, yerinde ölçüm, bilgisayar destekli simülasyon, kullanıcı anketi ve davranışsal gözlem tekniklerinin

birlikte kullanıldığı karma yöntemli bir yaklaşımla kurgulanmıştır. Seçili alanların ve muayene odalarının üç boyutlu modelleri çizilecek ve simülasyonlar aracılığıyla gün ışığı ve görsel konfor performansları analiz edilecektir. Bu sayede mekânsal organizasyon ve dolaşım özellikleri plan tabanlı analizlerle değerlendirilecektir. Elde edilen nesnel veriler, kullanıcıların mekânsal algı, konfor ve memnuniyetlerine ilişkin değerlendirmeleriyle karşılaştırılacak ve fiziksel çevre ile kullanıcı deneyimi arasındaki ilişkiler incelenecektir. Çalışmanın, çocuk polikliniklerinde mekânsal kalite ve kullanıcı deneyiminin değerlendirilmesine yönelik bir yöntemsel çerçeve sunması, ilgili literatüre katkı sağlaması ve çocuk odaklı sağlık mekânlarının tasarımına ilişkin değerlendirme ölçütlerinin geliştirilmesine katkı sağlaması beklenmektedir.

Anahtar Kelimeler: Çocuk poliklinikleri, mekânsal kalite, kullanıcı deneyimi, gün ışığı simülasyonu, çocuk odaklı sağlık mekânları.

STRATEGIC MANAGEMENT PRACTICES AND SERVICE DELIVERY EFFICIENCY IN NIGERIA'S PUBLIC SECTOR

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Abstract
This study examined the relationship between strategic management practices and service delivery efficiency in Nigeria's public sector. Despite decades of reform initiatives, public institutions continue to struggle with delays, poor quality, and low citizen satisfaction. Drawing on data from 420 respondents across federal and state ministries using structured questionnaires and semi-structured interviews, the research revealed moderate adoption of strategic management practices (mean score = 3.21 on a 5-point Likert scale). Multiple regression analysis demonstrated a strong positive and statistically significant impact of strategic management practices on service delivery efficiency ($\beta = 0.68$, $p < 0.01$), with strategy implementation and continuous monitoring emerging as the strongest predictors. Political interference and funding constraints were found to negatively moderate this relationship. The study further highlights that institutions with higher strategic alignment achieved up to 42% better citizen satisfaction scores. These findings underscore the transformative potential of business-oriented strategic tools in addressing public sector inefficiencies. The research recommends mandatory strategic planning training, performance dashboards, and reduced political meddling in operational decisions. Overall, the study contributes empirical evidence supporting the integration of strategic management principles to enhance governance and public value creation in developing economies like Nigeria.
Keywords: Strategic management, Service delivery, Public sector efficiency, Governance reform, Nigeria, Performance monitoring, Citizen Satisfaction.
JEL Classification: H11, M10, O10

FROM ARTIFICIAL INTELLIGENCE OUTPUTS TO AUDIT EVIDENCE: ASSESSING DATA RELIABILITY, OUTPUT ACCURACY, AND VERIFIABILITY IN ACCOUNTING AUDITING

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Abstract
The rapid integration of Artificial Intelligence (AI) into accounting and auditing is transforming the way auditors collect, process, analyze, and interpret financial information. AI-powered tools can enhance the efficiency of audit procedures by processing large and complex datasets, identifying anomalies, detecting patterns, and supporting risk assessment and professional judgment. However, the increasing reliance on AI-generated outputs raises a fundamental question concerning their suitability as audit evidence: To what extent can auditors rely on AI-generated information as accurate, reliable, and verifiable evidence?
This study examines the reliability of AI-generated outputs within the context of accounting auditing, with particular emphasis on three dimensions: data reliability, output accuracy, and verifiability. It explores whether the quality of data provided to AI systems, the accuracy and consistency of their outputs, and the ability of auditors to independently verify AI-generated results influence the perceived reliability of such outputs as audit evidence. The study also considers the importance of human oversight and professional skepticism in mitigating the risks associated with excessive reliance on AI-based auditing tools.
A quantitative research approach is proposed, using a structured questionnaire targeting professional auditors and accounting practitioners with experience in, or awareness of, AI-enabled auditing technologies. The proposed conceptual framework examines the relationships between the reliability of input data, AI output accuracy, output verifiability, and the reliability of AI-generated audit evidence. The study further investigates whether auditor professional skepticism and human oversight strengthen the assessment of AI-generated outputs before their incorporation into audit procedures.
The study is expected to contribute to the emerging literature on AI-enabled auditing by developing an evidence-based framework for evaluating when and under what conditions AI-generated outputs can be considered sufficiently reliable for audit purposes. It emphasizes that technological efficiency alone cannot establish the evidential value of AI outputs; rather, reliability requires a combination of high-quality data, accurate outputs, transparency, verifiability, and appropriate human professional judgment. The findings are expected to provide practical implications for auditors, accounting firms, regulators, and professional bodies seeking to establish effective governance mechanisms for the responsible and reliable use of AI in auditing.
Keywords: Artificial Intelligence; AI-Generated Outputs; Audit Evidence; Data Reliability; Output Accuracy; Verifiability; AI in Auditing; Professional Skepticism; Human Oversight; Accounting Auditing.

DIGITAL TRANSFORMATION AND ENHANCING THE RESILIENCE OF VIETNAMESE SMALL AND MEDIUM-SIZED ENTERPRISES AMID SUPPLY CHAIN DISRUPTIONS

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Abstract: Digital transformation in small and medium-sized enterprises (SMEs) is often approached as a process of technological innovation, operational optimization, or market expansion. Yet, in a context where external shocks increasingly affect transportation, input costs, cash flows, and supply chain continuity, this perspective needs to be broadened by treating digital transformation as a component of enterprise resilience. This article employs secondary document analysis and cross-source synthesis of materials on national digital transformation, SME digital transformation in Vietnam, South Korea's experience, digital supply chain finance, and state-management documents concerning trade and logistics risks. The analysis yields three main findings. First, the bottlenecks faced by Vietnamese SMEs do not lie solely in technology ownership, but also in data governance capacity, process standardization, system integration, digital human resources, and cybersecurity. Second, when supply chains are disrupted, digital capabilities can help firms track goods flows, update information, reconfigure plans, manage cash flows, and reduce information asymmetry; however, their effectiveness depends on data quality and the degree of connectivity among actors. Third, digital supply chain finance offers a noteworthy mechanism for linking transaction data with access to capital, although existing international evidence does not justify mechanically generalizing these effects to all Vietnamese SMEs. On this basis, the article proposes a resilience-oriented digital transformation framework consisting of five layers of capability: governance foundations, data, supply chain operations, digital finance, and risk management. The framework emphasizes that digital transformation should begin with concrete business problems and actual risks rather than with technology acquisition.
Keywords: digital transformation; small and medium-sized enterprises; resilience; supply chain; digital supply chain finance; Vietnam.

1. Introduction

Digital transformation has moved beyond the realm of a purely technical choice. In the policy documents and studies used in this article, digital transformation is understood in a broader sense: data and digital technologies alter business models, processes, products, and organizational modes of operation, rather than merely shifting documents or tasks from physical to electronic environments (Ministry of Information and Communications, 2020; Nguyen Thi Huong, 2025). This distinction is directly relevant to the business sector. An enterprise may use accounting software, online sales channels, or digital communication platforms and still fall short of genuine digital transformation if its data remain fragmented, its processes are not standardized, and managerial decisions are disconnected from information systems. Technology alone is not enough.

For Vietnamese SMEs, the issue is even more apparent. The Digital Transformation Handbook for Enterprises in Vietnam, developed by the Ministry of Planning and Investment with support from USAID/LinkSME, identifies a recurring set of barriers: high investment costs, limited information technology infrastructure, difficulties in accessing cybersecurity solutions, constrained digital transformation resources, unstandardized business processes and supply chains, and limited access to information on digital technologies (Ministry of Planning and Investment & USAID/LinkSME, 2021). Nguyen Thi My Hang and Nguyen Thi Minh Thuy (2022), in their analysis of digital transformation among Vietnamese SMEs, identify a similar structure of constraints. The bottleneck, therefore, does not lie in a single variable. It is systemic.

Under relatively stable business conditions, these limitations may appear as higher costs, slower processing, or restricted scalability. Once an external shock occurs, however, their consequences change qualitatively. A 2026 official dispatch issued by the Agency of Foreign Trade concerning measures to mitigate the effects of conflict involving the United States, Israel, and Iran warned of possible increases in fuel prices, freight charges, transportation times, and logistics costs; it also recommended that firms closely monitor developments, exchange information, proactively plan production, import-export activities, and transportation, and prepare risk-prevention scenarios (Agency of Foreign Trade, 2026).

This document is not quantitative evidence of actual impacts on individual SMEs. Nevertheless, it clarifies a managerial requirement: firms must be able to identify change early, process information rapidly, and adjust operations under uncertainty.

This gives rise to the central research question of the article: how can digital transformation be situated within the resilience capacity of Vietnamese SMEs, and under what conditions can digital capabilities genuinely support firms in responding to supply chain disruptions? The article does not estimate causal relationships using firm-level Vietnamese data. No overreach. Instead, it conducts secondary document analysis, compares available evidence, and develops a deliberately bounded analytical framework connecting three strands that are often discussed separately: SME digital transformation, supply chain management, and access to finance in a digital environment.

2. Analytical Framework and Research Method

Conceptually, this article approaches digital transformation as a process of restructuring operations on the basis of data and digital technologies. This understanding is consistent with national digital-transformation materials, in which digitization refers to converting information into digital form; digital technology adoption simplifies and optimizes operations; and digital transformation, at a higher level, changes organizational models and modes of operation (Ministry of Information and Communications, 2020). At the national level, Vietnam's digital transformation program is organized around three pillars: digital government, digital economy, and digital society. At the enterprise level, the corresponding logic is a shift from isolated applications toward the integration of data, processes, and managerial decision-making.

The concept of "resilience" is used here in an operational sense: the capacity of an enterprise to maintain core functions, adapt, and reconfigure operations when input conditions, transportation, markets, or finance fluctuate. The article does not construct a new resilience scale, nor does it attribute effects to digital transformation that the source materials do not substantiate. Instead, the relationship is identified through mechanisms that the documents allow us to observe: greater information visibility, data standardization and interoperability, decision support, optimization of goods and cash flows, improved access to finance, and stronger coordination among actors in the chain.

The research method is problem-oriented secondary document analysis. The principal sources include materials on national digital transformation management; the Digital Transformation Handbook for Enterprises in Vietnam; studies on the state of digital transformation among Vietnamese SMEs; research on South Korea's experience; international research on digital supply chain finance; and state-management documents relating to trade and transportation risks in the context of regional conflict. These sources differ in objectives, methods, and scope. Accordingly, the article does not pool statistics across sources, does not treat evidence from listed Chinese firms as direct evidence for Vietnam, and does not use policy documents as causal evidence. This principle is maintained throughout.

3. Digital Transformation of Vietnamese SMEs: From Technology Adoption to Management Capability

The literature on Vietnamese SMEs reveals a notable paradox. On the one hand, firms can adopt relatively quickly those solutions that are directly connected to the market, such as omnichannel sales, digital marketing, customer relationship management, or business software. On the other hand, the internal foundations required for comprehensive transformation remain weaker: internal governance is incomplete, technology systems are difficult to integrate, technology-related human resources are limited, data are not yet treated as a managerial asset, and cybersecurity has not received adequate attention (Ministry of Planning and Investment & USAID/LinkSME, 2021). Thus, "using technology" and "possessing digital capability" are not the same thing.

Survey data cited by Nguyen Thi My Hang and Nguyen Thi Minh Thuy (2022) from the Vietnam Chamber of Commerce and Industry show that investment cost was the most frequently mentioned barrier, at 55.6%; this was followed by underdeveloped information technology infrastructure at 38.9%, difficulty accessing risk and cybersecurity solutions at 33.9%, limited digital transformation resources at 32.3%, and difficulty accessing information about digital technologies at 30.4%. These figures come from a 2020 survey and should not be presented as the state of affairs in 2026. Their value lies in identifying the structure of constraints. Importantly, alongside cost and infrastructure, problems involving processes, supply chains, human resources, and information also emerge. These are the factors that determine whether technology can be converted into organizational capability.

From a resilience perspective, the most serious weakness is not necessarily the absence of a specific software package. It is the disconnect between data and action. When inventory data are not linked to orders; order data are not connected to transportation planning; receivables information is not reflected promptly in cash-flow forecasts; or supplier information is managed in isolated files, firms struggle to recognize their exposure to a shock. One beat too late. In normal conditions, such delay may be compensated for by individual experience. In a crisis, it narrows the response window.

For this reason, the digital transformation roadmap for SMEs should be understood through the logic of capability maturity. The handbook by the Ministry of Planning and Investment and USAID/LinkSME (2021) proposes a roadmap beginning with a preparation stage and continuing through subsequent transformation stages, while linking implementation to assessments of digital readiness. The strength of this approach lies in placing technology within a process rather than treating digital transformation as a procurement project. Drawing on South Korea's experience, Nguyen Thi Huong (2025) likewise emphasizes the importance of roadmaps, infrastructure, data, digital capability, and workforce training and retraining. The two groups of sources differ in context, but converge on one point: digital transformation requires institutional-managerial foundations and the gradual accumulation of capability over time.

4. Digital Transformation as a Component of Supply Chain Resilience

Supply chains place firms within networks of mutual dependence. A disruption in transportation, energy, border procedures, suppliers, or financial markets can be transmitted to a firm through prices, delivery times, payment capacity, and inventories. The 2026 dispatch of the Agency of Foreign Trade specifically noted the risk of higher fuel prices and freight costs, cargo flights being rerouted, and transportation through the Strait of Hormuz being delayed or forced onto alternative routes, thereby increasing time and cost. The recommendations of the management authority focus on information monitoring, coordination with ministries and agencies, proactive planning, and preventive scenarios. Translated into the language of enterprise capability, these requirements reveal four important digital functions.

The first is visibility. Digital data only contribute to resilience when firms can see the status of core variables: orders, inventory, supplier progress, transport schedules, receivables and payables, cash flows, and bottlenecks. Digitizing a document without linking it to decision-making creates data but not visibility. For SMEs, therefore, the priority is not necessarily the most sophisticated technology. The first requirement is data that are sufficiently clean, consistent, and timely.

The second is coordination. When information exists in separate "islands" across sales, procurement, warehousing, accounting, and transportation, firms respond department by department. Supply chains do not operate department by department. Digital platforms, when implemented on standardized processes, can reduce communication lags and create a shared source of information. Yet the Digital Transformation Handbook for SMEs itself identifies unstandardized processes and supply chains as a common barrier (Ministry of Planning and Investment & USAID/LinkSME, 2021). Digital integration must therefore proceed together with process redesign. The order cannot be reversed.

The third is reconfiguration capability. During a logistics shock, firms may need to change transport routes, suppliers, import schedules, safety-stock levels, or payment terms. Digital systems do not automatically generate optimal options if input data are poor or if firms have no viable alternatives. They can, however, reduce the time required to consolidate information, compare scenarios, and track the consequences of decisions. Research on the "digital supply chain twin," cited by He and Liu (2025) in their review, indicates that digital technologies are being used to manage disruption risks and supply chain resilience. This is evidence of a technological direction of development, not evidence that every SME needs to deploy an advanced digital-twin model.

The fourth is protection. As operations become more dependent on data and platforms, digital risk becomes operational risk. Studies of Vietnamese SMEs have documented difficulties in accessing cybersecurity solutions and shortcomings in awareness and information-risk management policies (Ministry of Planning and Investment & USAID/LinkSME, 2021; Nguyen Thi My Hang & Nguyen Thi Minh Thuy, 2022). A highly integrated system without backup, authorization, authentication, and incident-response procedures can create a new point of failure. Digital transformation can therefore strengthen resilience while simultaneously expanding the risk surface that must be governed.

5. Digital Supply Chain Finance: Connecting Data with Access to Capital

A supply chain shock is not only a problem of goods. It quickly becomes a cash-flow problem. Longer transportation times keep capital tied up in inventory for longer; higher freight and fuel costs increase working-capital needs; and delayed payments widen financing gaps. For SMEs, this is particularly sensitive because access to credit is often shaped by collateral, financial history, and information asymmetry.

The study by He and Liu (2025), based on listed SRDI enterprises in China's electronics and machinery industries over the 2013-2020 period, provides noteworthy empirical evidence. The authors find that digital supply chain finance (DSCF) is associated with the alleviation of financing constraints among the firms studied, with effects varying by industry. The mechanisms discussed include the use of blockchain to increase transparency and data sharing, AI and alternative data to support credit-risk assessment, IoT to improve monitoring, and digital platforms to enhance information and capital flows (He & Liu, 2025).

This evidence must be interpreted within its proper limits. The sample consists of listed SRDI firms in China, concentrated in two industries and a specific period. He and Liu (2025) themselves acknowledge limitations in generalizing the findings to unlisted firms, other industries, or other countries. It therefore cannot be concluded from this study that DSCF will necessarily reduce financing constraints for Vietnamese SMEs to the same extent. What can be extracted is the mechanism: when transaction data, inventories, receivables, and supply chain relationships become more transparent, structured, and credible, financial institutions gain additional grounds for evaluating firms beyond traditional criteria.

This point returns the discussion to the foundations of digital transformation. If firms have not standardized data, lack verifiable transaction histories, or operate with systems that cannot interoperate across parties, digital supply chain finance is unlikely to function effectively. He and Liu (2025) emphasize problems such as inaccurate data, lack of standardization, and difficulty integrating heterogeneous data sources. Data are therefore not only inputs for operational management. They can also become part of the infrastructure of trust. This is a crucial link.

For Vietnamese SMEs, a cautious implication is to prioritize the traceability and standardization of financially relevant data: contracts, invoices, orders, delivery records, inventory, receivables, and payment histories. When such data are managed consistently, firms can improve internal control while also creating conditions for transaction-based financing models. However, moving from technical feasibility to actual access to finance further requires a legal framework, data standards, consent-based sharing mechanisms, data protection, and appropriate risk-governance models within financial institutions. The available sources are not sufficient to quantify the effect of each of these conditions in Vietnam.

6. A Resilience-Oriented Digital Transformation Framework for Vietnamese SMEs

Based on the foregoing analysis, this article proposes a framework consisting of five layers of capability. This is a synthesis derived from the literature, not an empirically validated measurement scale. The first layer is the governance foundation: defining business problems, process ownership, data responsibilities, risk tolerance, and the investment roadmap. Without this layer, digital transformation can easily become a collection of disconnected technology projects. The second layer is data: standardizing master data, entry rules, partner and product coding, access rights, backup, and connectivity. Data must be usable. That is the minimum condition.

The third layer is digital supply chain operations. The objective is not to automate every activity, but to create visibility and coordination at points that matter most for continuity: inventory, suppliers, orders, transportation, lead times, and deviation alerts. For resource-constrained firms, implementation should follow the materiality of risk. A firm heavily dependent on imported inputs should prioritize supplier data, lead times, and inventory; an exporting firm should prioritize orders, vessel schedules, documentation, and receivables. There is no single configuration for all SMEs.

The fourth layer is digital finance linked to the supply chain. Its objective is to connect operational data with working-capital management: scenario-based cash-flow forecasting, monitoring receivables and payables, identifying financing needs when transportation times lengthen, and gradually preparing data for supply-chain finance products. The evidence from He and Liu (2025) suggests a role for DSCF in reducing information asymmetry and financing constraints, but its application in Vietnam requires separate empirical testing.

The fifth layer is digital risk management and business continuity. At a minimum, firms need backup, authorization, authentication, technology-vendor management, data-recovery mechanisms, and alternative operating procedures for system disruptions. External risk-warning systems must also be linked to accountable personnel and specific actions. The recommendation to "closely monitor" only becomes meaningful when a firm clearly identifies which indicators to monitor, what thresholds trigger action, who decides, and what alternative scenario will be activated.

These five layers are sequentially related but not strictly linear. SMEs may implement several components at the same time, yet priorities should move from business problems to data, from data to processes, and only then to more complex technologies. South Korea's experience, as synthesized by Nguyen Thi Huong (2025), shows that digital transformation at the national level requires infrastructure, data, human resources, and a clear roadmap; when scaled down to the firm level, this lesson retains its value as a principle. Digital capability is not created by a single investment. It accumulates.

7. Policy and Management Implications

At the firm level, the first implication is to change the criterion used to select digital transformation projects. Instead of asking "Which software should we buy?", enterprises need to ask "Which point of failure causes the greatest loss when disruption occurs?" This reframes digital transformation around the relationship between technology and organizational capability. Projects can start small: standardizing inventory data, linking orders to procurement planning, establishing a cash-flow dashboard, or digitizing supplier records. But they must connect to decisions.

At the policy level, support for SMEs should avoid an approach dominated by lists of technology solutions. The barriers identified in Vietnamese sources indicate that firms simultaneously require process consulting, readiness assessment, workforce training, cybersecurity support, and improved access to financial resources (Ministry of Planning and Investment & USAID/LinkSME, 2021; Nguyen Thi My Hang & Nguyen Thi Minh Thuy, 2022). Digital transformation support should therefore be designed as "capability packages," differentiated by firm size, industry, and maturity level, rather than assuming that all SMEs have the same needs.

At the ecosystem level, data standards and interoperability should be treated as soft infrastructure. Digital supply chain finance can develop only when data among firms, logistics partners, platforms, and financial institutions can be authenticated, shared, and used within a secure framework. He and Liu (2025) identify transparency and data sharing as central mechanisms of DSCF while also highlighting the problems of insufficient standardization and data integration. For Vietnam, this is an area that requires deeper empirical research before large-scale interventions are designed.

Finally, during trade and logistics shocks, state-management agencies can increase the value of public information by standardizing and digitizing warnings according to risk category, transport route, market, and commodity group. This would help firms move more quickly from "knowing that disruption exists" to "knowing where that disruption affects us." The 2026 dispatch of the Agency of Foreign Trade already emphasizes monitoring, information exchange, and timely updates. The next step in digital governance is to make such information capable of being integrated into enterprise decision-making processes.

8. Conclusion

Digital transformation among Vietnamese SMEs needs to be understood as serving a broader purpose than increasing efficiency or expanding sales channels. In a volatile business environment, its important value lies in enabling firms to see earlier, coordinate faster, reconfigure on a more informed basis, and manage cash flows more rigorously. Yet this occurs only when data, processes, people, and risk governance are developed together with technology.

The documents analyzed show that Vietnamese SMEs still face bottlenecks involving cost, infrastructure, human resources, process standardization, data governance, and cybersecurity. International evidence on digital supply chain finance suggests that data can be used to reduce information asymmetry and support access to capital, but such evidence cannot be directly generalized to Vietnam. The five-layer framework proposed in this article should therefore be viewed as a research framework and managerial orientation that requires further testing using Vietnamese enterprise data, particularly across industries, firm sizes, and degrees of dependence on international supply chains.

The key issue is sequence. Digital transformation should not begin with the most expensive technology, but with the most important risk and decision. When firms correctly identify what must be observed,

standardize the relevant data, connect processes, and establish response mechanisms, technology becomes capability. Digital transformation then does more than help firms operate faster. It helps them remain standing.

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BLOCKCHAIN TECHNOLOGY AND THE TRANSFORMATION OF FINANCIAL REPORTING AND AUDITING

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ABSTRACT

The rapid development of digital technologies is transforming the accounting profession and changing the traditional approaches to financial reporting and auditing. Among emerging technologies, blockchain has attracted significant attention because of its potential to enhance transparency, reliability, traceability and security in accounting information systems. This paper examines the role of blockchain technology in transforming financial reporting and auditing practices. It explores how distributed ledger technology can facilitate real-time recording of transactions, reduce the risk of unauthorised alterations, improve the availability of reliable financial information and strengthen audit trails. The paper further considers the implications of blockchain adoption for auditors, accountants and organisations, particularly in relation to transaction verification, internal controls, fraud detection and financial statement reliability. Despite these potential benefits, challenges such as high implementation costs, inadequate technical expertise, regulatory uncertainty, cybersecurity concerns and resistance to technological change may limit widespread adoption, particularly among developing economies. The paper adopts a conceptual review approach, drawing on relevant accounting and technology literature to examine the relationship between blockchain technology and contemporary financial reporting and auditing. The paper argues that effective integration of blockchain into accounting systems could improve the quality and credibility of financial information while reducing some traditional reporting and auditing risks. It recommends investment in digital accounting skills, appropriate regulatory frameworks, cybersecurity infrastructure and continuous professional development for accounting professionals. The study concludes that blockchain represents an important technological development capable of reshaping financial reporting and auditing, provided that its implementation is supported by appropriate institutional and professional frameworks.

Keywords: Blockchain Technology, Financial Reporting, Auditing, Accounting Information Systems, Transparency, Audit Quality.

DETERMINANTS OF SMART FACILITIES MANAGEMENT TECHNOLOGY ADOPTION AMONG PRACTITIONERS IN ABUJA, NIGERIA

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Abstract
This study examines the determinants and barriers affecting Smart Facilities Management (Smart FM) technology adoption among facilities management practitioners in Abuja, Nigeria. Motivated by the persistent contradiction between high awareness and low actual deployment of Smart FM technologies in developing economies, the study argues that infrastructural deficits, particularly unstable electricity supply and limited ICT infrastructure, function as conditioning variables that weaken the conversion of adoption intention into actual implementation. A quantitative cross-sectional survey design was employed, collecting data from 224 professionally registered FM practitioners, estate surveyors, and built environment professionals in the Federal Capital Territory. Ordinary Least Squares multiple regression analysis revealed that cognitive and organisational determinants significantly influence adoption intentions, explaining 38.4% and 56.7% of the variance, respectively. However, environmental-context variables added a further 8.1% to the explained variance, with ICT infrastructure emerging as the second-strongest predictor of adoption ($\beta = .291$, $p < .001$) and high implementation cost recording a significant negative effect ($\beta = -.173$, $p = .007$). The findings demonstrate that positive adoption intentions alone are insufficient to guarantee deployment where infrastructural instability and financial limitations remain severe. The study proposes Solar-Augmented IoT Architecture (SAIA) as a localised deployment strategy for overcoming power-related constraints and introduces a contextualised cost–benefit framework for evaluating solar-supported Smart FM systems. The paper contributes to Smart FM literature by extending technology adoption models to incorporate infrastructural conditioning factors within developing economy contexts.
Keywords: Smart Facilities Management, technology adoption, infrastructure conditioning, Solar-Augmented IoT Architecture, Nigeria, TOE framework

THE MODERATING ROLE OF BOARD FINANCIAL EXPERTISE IN THE RELATIONSHIP BETWEEN BOARD ATTRIBUTES AND CORPORATE TAX AVOIDANCE: EVIDENCE FROM NIGERIA

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ABSTRACT
Grounded in Agency Theory and Upper Echelons Theory, this study re-conceptualizes governance effectiveness as competence-driven rather than purely structural. We argue that beyond board size, independence, busyness, and meeting frequency, directors' financial expertise critically shapes the board's capacity to monitor complex financial decisions and influence corporate tax avoidance. Accordingly, the study examines whether board financial expertise moderates the relationship between board attributes and corporate tax avoidance among Nigerian listed firms. Using a panel dataset of 1,243 firm-year observations from 113 firms listed on the Nigerian Exchange over the period 2013–2023, we employ fixed-effects regression with cluster-robust standard errors, complemented by Panel-Corrected Standard Errors (PCSE) for robustness. Corporate tax avoidance is measured using the long-run cash effective tax rate (LCETR) and long-run GAAP effective tax rate (LGETR). The findings reveal that board size and independence are associated with lower tax avoidance, while board busyness and meeting frequency exhibit mixed effects. Crucially, board financial expertise significantly moderates these relationships, demonstrating that structural governance mechanisms are effective only when supported by relevant financial competence. By integrating structural and human capital perspectives within an emerging economy context, this study extends corporate governance theory and provides evidence-based support for competence-oriented board reforms.

Keywords: Board Financial Expertise; Board Busyness; Corporate Governance; Corporate Tax Avoidance; Nigeria

PREPARATION OF FINANCIAL REPORTS AT CV DEWA BASED ON MICRO, SMALL AND MEDIUM ENTERPRISES FINANCIAL ACCOUNTING STANDARDS (SAK EMKM)

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ABSTRACT
Preparation of Financial Statements at CV Dewa Based on Micro, Small and Medium Financial Accounting Standards (SAK EMKM). Financial statements are reports that show conditions and provide financial information at this time or within a certain period. This study aims to facilitate MSMEs in compiling financial reports in accordance with SAK EMKM. The purpose of this study is to find out how the preparation of financial statements that have been made by CV Dewa and what obstacles are faced in preparing financial statements based on SAK EMKM. This research uses a qualitative descriptive approach with a case study method, for data collection is carried out by field research and literature. From the results of calculations using the Dean J. Champion formula, it shows that the preparation of financial statements is 100% (very appropriate), profit and loss statements are 100% (very appropriate), notes to financial statements are 0% (not appropriate). The conclusion in this study, the notes on the financial statements are not in accordance with the provisions of SAK EMKM because CV Dewa did not compile notes on the financial statements. Meanwhile, CV Dewa statement of financial position has not recorded current accounts, deposits and inventories.
Keywords: Financial Report, account, deposit, inventories, SAK EMKM

SWOT ANALYSIS IN DETERMINING THE SALES STRATEGY OF CAR PRODUCTS AT THE MITSUBISHI DEALER PT MAHAKAM BERLIAN SAMJAYA IN SAMARINDA CITY

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ABSTRACT
Companies need to recognize their strengths and weaknesses in the competition. This will really help companies recognize themselves, as well as take advantage of every existing opportunity and avoid or minimize threats. A company can develop a competitive strategy by means of a SWOT analysis, namely looking for a match between the company's internal strengths and external strengths. The elements that comprise SWOT analysis are: strength (strength), weakness (weakness), opportunities (opportunity) and threats (threat). This research aims to determine and analyze the influence of SWOT on car sales strategies at the Mitsubishi dealer PT Mahakam Berlian Samjaya, Samarinda City. This research was conducted at PT Mahakam Berlian Samjaya. This study was limited to strength (strengths), weakness (weaknesses), chance (opportunities), and threats (threats). The data collection techniques used in this research are field research and library research. The analysis tools used are the internal external matrix, SWOT matrix and SWOT diagram. The results of the SWOT analysis show that the position of the car marketing strategy at PT Mahakam Berlian Samjaya is in Quadrant I, where the right strategy to be implemented by PT Mahakam Berlian Samjaya in increasing its sales turnover is an aggressive strategy by supporting aggressive growth policies (growth oriented strategy). The condition of PT Mahakam Berlian Samjaya is in the first quadrant, this shows that the company is in a very favorable condition because it has strengths so it can seize several opportunities, namely the high public interest in owning cars, advances in industrial technology, high consumer confidence in the quality of PT Mahakam Berlian Samjaya products and has a good image.
Keywords : Sales Strategy, SWOT Analysis, Strengths, Weakness, Opportunities, Threats, Growth Oriented Strategy

IMPACT OF WASTE MANAGEMENT PRACTICES ON RESIDENTIAL RENTAL VALUES IN BAUCHI METROPOLIS

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ABSTRACT
Waste Management (WM) entails generation, collection, handling, transfer, disposal, reuse, recycling, reclaim and auditing of waste at a minimal cost this study examined the effect of waste management practices on residential rental values in Bauchi Metropolis, focusing on; current waste management practices, residential rental values, perception of tenants and landlords on the relationship between waste management rental values and effect of waste management practice on residential rental values. Data were collected from 357 respondents and 342 where retrieved and analyzed using descriptive statistics, and multiple regression. The findings revealed that environmentally oriented practices particularly recycling to improve environmental quality (Mean = 3.80), pollution prevention (3.75), and avoiding environmental pollution (3.71) were rated highest by residents. Conversely, preserving legal dumpsites near houses (2.50) and incinerator availability (2.58) were strongly rejected. Rental values showed clear stratification by property type, with duplexes commanding the highest rents (Mean = 3.81) and mud houses the lowest (1.35). Both tenants and landlords perceived waste management as value-relevant: landlords viewed it as asset protection (3.94), while tenants considered it a fundamental right (3.94) and hygiene factor (3.89). The regression model was significant ($F(5, 336) = 69.725$, $p < .001$, $R^2 = .510$), with waste management collection ($\beta = .381$), sanitation ($\beta = .337$), and recycling ($\beta = .298$) positively predicting rental values, while landfill proximity ($\beta = –.271$) and illegal dumping ($\beta = –.182$) significantly reduced them. These results confirm that waste management is economically capitalized into the Bauchi rental market, providing empirical support for integrating waste service delivery into urban housing policy.
Keywords: waste management, residential rental values, rental values.

1. INTRODUCTION
Waste Management (WM) involves the generation, collection, handling, transfer, disposal, reuse, recycling, reclaim, and auditing of waste at minimal cost (Omotosho, 2020). Global waste generation has increased from 1.3 billion tons in 2010 to 2.0 billion tons in 2016 and is projected to reach 2.2 billion tons by 2025, 2.59 billion tons by 2030, and 3.4–3.8 billion tons by 2050 (Barbara & Sabine, 2023). In 2016, high-income countries generated 0.683 billion tons compared with 0.655 billion tons by lower-middle-income, 0.586 billion tons by upper-middle-income, and 0.093 billion tons by low-income nations (Barbara & Sabine, 2023). The USA and China alone generated 0.28–0.29 and 0.24–0.32 billion tons respectively (Awasthi et al., 2022). This rapid increase has intensified environmental and public health concerns, prompting governments to adopt strategies that reduce toxicity, gaseous emissions, and related health risks (Zhang et al., 2022). Despite these efforts, over 100 million tons of the 2 billion tons of waste generated globally continue to be dumped illegally in unregulated areas, with untreated sewage and mixed waste polluting freshwater and landfills (Barbara & Sabine, 2023).
Municipal Solid Waste (MSW) collection is the most visible and cost-intensive component of integrated waste management, consuming 50–70% of municipal budgets (Wilson et al., 2022). The literature debates whether public or private sector delivery is more efficient. Bel and Warner (2018) found that

private delivery is generally associated with lower costs, though the difference is modest and context-dependent. Recycling is also central to modern WM and the circular economy, as it conserves resources and reduces greenhouse gas emissions (Fei et al., 2016). However, its effectiveness depends on technical infrastructure. Single-stream collection increases participation but often leads to higher contamination, while advanced technologies like optical sorters and AI-powered robots are improving sorting accuracy and reducing costs (Ragaert et al., 2017).

The siting of landfills presents another challenge due to negative externalities such as leachate, odor, noise, greenhouse gases, and traffic. Studies consistently show that residential properties within 0.5–3 miles of landfill sites experience reduced values due to these disamenities, with the impact diminishing as distance increasesa "distance decay" effect (Nelson et al., 2022; Ready, 2015). Proper closure and remediation can lessen or reverse this effect, particularly when land is converted into public parks (Oluwunmi et al., 2020). The 1987 United Church of Christ report was the first to demonstrate that race is the most significant predictor of proximity to hazardous waste facilities, including landfills (Bullard, 2020).

Illegal dumping, or fly-tipping, poses serious environmental and public health risks. The primary driver is cost avoidance, as legal disposal of construction and hazardous waste incurs tipping and transportation fees (Gray & Shimshack, 2021). Dumped waste contaminates soil and groundwater, attracts disease-carrying vermin, and facilitates mosquito breeding in stagnant water (Mallo et al., 2017). Municipalities incur high cleanup costs that divert funds from education and public safety, while persistent dumping reduces property values and deters business investment and tourism (Esper et al., 2020). Research also links visible disorder from illegal dumping to increased fear of crime and weakened social controls (Sampson & Raudenbush, 2019).

Sanitation policy has evolved from centralized sewer-based systems to demand-driven approaches that emphasize equity, financing, and resource recovery (Evans, 2019). A major challenge is underfunding compared to water supply, with financing options including public investment, cross-subsidies, output-based aid, and microfinance (Baba et al., 2020; Tremolet et al., 2020). While private sector participation can improve efficiency, it requires strong regulation to ensure accountability and equity for low-income populations (Oluwunmi et al., 2020).

The relationship between waste management practices and property values remains under-researched, particularly in secondary cities like Bauchi, Nigeria. Rapid urbanization has outpaced the development of waste management infrastructure, affecting environmental quality, public health, and economic vitality factors that directly influence residential property values (Baba et al., 2020). Empirical evidence shows that proximity to landfills lowers property values due to odor, noise, visual blight, and perceived health risks (Nelson et al., 2022; Ready, 2015), while illegal dumping contributes to environmental contamination, disease outbreaks, and community decline (Mallo et al., 2017; Esper et al., 2020).

In Nigeria, most studies have focused on major cities such as Lagos and Abuja, leaving a gap in understanding how waste management practices affect property values in secondary cities like Bauchi. Bauchi metropolis faces challenges of inadequate collection services, indiscriminate dumping, and weak sanitation infrastructure, yet there is no empirical evidence on how these practices influence residential rental values. This knowledge gap limits the ability of policymakers to design effective, context-specific waste management interventions that can enhance both environmental quality and property market performance.

Therefore, this study assesses the impact of waste management practices on residential rental values in Bauchi metropolis, with a view to identifying the most effective practices that can improve property values and promote sustainable urban development.

The aim of this study is to examine the impact of waste management practices on residential rental values in Bauchi metropolis, with a view to identifying how proper and improper waste disposal influences property demand and pricing. Specifically, the objectives are:

- To assess the current waste management practices in residential areas of Bauchi metropolis.
- To determine the residential rental values in the study area
- To evaluate the perception of tenants and landlords on the relationship between waste management rental values.
- To assess the effect of waste management practice on residential rental values in the study area.

2. LITERATURE REVIEW

2.1CONCEPT OF WASTE MANAGEMENT STRATEGIES

Waste management is guided by the 3Rs hierarchy: Reduction, Reuse, and Recycling*, arranged in ascending order of environmental impact (Hongping, 2021).

2.1.1 Waste Reduction: The most effective method, as it minimizes waste generation and cuts transport, recycling, and disposal costs (Hongping, 2021). Key measures include government legislation (Tam, 2018), project design solutions, effective Waste Management Systems (WMS) with five elements policy, planning, implementation, checking, and review and low-waste technologies (Hongping, 2021).

2.1.2 Waste Reuse: Using materials more than once for the same or new function, such as formwork or cut steel bars (Duran, Lenihan & O'Regan, 2016). It is the second most desirable option due to minimal processing and energy use. Effectiveness depends largely on stakeholders' attitudes and efficiency rather than the material itself (Hongping, 2021).

2.1.3 Waste Recycling: Converting waste into new materials when reduction and reuse are not feasible. Benefits include reduced demand for new resources, lower transport and energy costs, less landfill use, land preservation, and improved environmental quality (Tam, 2018). Competitiveness of recycled materials depends on transport facilities, population density, and cost-quality parity with virgin materials (Lauritzen in Hongping, 2021; Tam, 2016; Inyang, 2003).

2.1.4 Waste Disposal: Landfills or public fills are the last option in the hierarchy. Uncontrolled and illegal dumping is common in many economies due to extra disposal costs under the polluter-pay-principle (Hao et al., 2018; Begum et al., 2017). Waste charging schemes have been shown to reduce landfill waste by about 65% (Hao et al., 2018), though excessive charges may reduce stakeholder participation.

2.2 WASTE MANAGEMENT PRACTICE

2.2.1 Municipal Solid Waste (MSW) Collection Systems: MSW collection is the most visible and cost-intensive component of WM, often accounting for 50–70% of budgets (Wilson et al., 2022). Research models it as a Capacitated Vehicle Routing Problem to optimize routes and minimize costs (Scheinberg et al., 2020; Nuortio et al., 2016). Smart waste management using IoT sensors enables dynamic routing, reducing fuel use and emissions (Abumere, 2019). Alternative fuel vehicles are also explored to cut greenhouse gases and noise (Erdem, 2015). Policy instruments such as Pay-As-You-Throw (PAYT) provide economic incentives for waste reduction and higher recycling rates (Skumatz, 2022; U.S. EPA, 2006). EU directives have shifted systems toward source-segregated collection (Scheinberg et al., 2020). Citizen participation and integration of the informal waste-picking sector are critical for success (Timlett & Williams, 2018; Wilson et al., 2016).

2.2.2 Recycling Recycling: diverts waste from landfills and conserves resources, but its efficiency depends on infrastructure and public participation. Single-stream collection increases tonnage but raises contamination, while dual- and multi-stream systems improve quality (Brooks et al., 2018). Advanced technologies like NIR spectroscopy and AI robots enhance sorting accuracy (Ragaert et al., 2017). Behavior is influenced by convenience, knowledge, social norms, and incentives (Finnveden et al., 2019; Schultz et al., 2018). The China National Sword policy (2018) exposed the fragility of export-dependent recycling markets (Brooks et al., 2018). Extended Producer Responsibility (EPR) shifts responsibility to producers and promotes design for recyclability (OECD, 2016).

22.3 Landfill Proximity: Landfills generate odors, greenhouse gases, and health risks. Literature confirms a strong correlation between landfill proximity and socio-economic disadvantage (Bullard, 2020). Epidemiological studies report small but significant increases in adverse birth outcomes near landfills (Vrijheid, 2020; Elliott et al., 2021), alongside respiratory symptoms and stress from odor (Bullard, 2020). Property values show a consistent "distance decay" effect, with discounts diminishing as distance increases (Ready, 2015). Closure and remediation can reverse negative effects (Elliott et al., 2021).

2.2.4 Illegal Dumping: Illegal dumping is driven by cost avoidance and weak enforcement (Gray & Shimshack, 2021; Nellemann et al., 2016). Lack of affordable legal disposal options and weak social norms also contribute (Matsumoto & Takeuchi, 2021; Keizer et al., 2018). Effective strategies include increased surveillance, community clean-ups, and making legal disposal accessible (Matsumoto & Takeuchi, 2021; US EPA, 2021; Esper et al., 2020).

2.2.5 Sanitation Policies: Sanitation policy has shifted from centralized sewer systems to demand-driven approaches like Community-Led Total Sanitation (CLTS) and Sanitation Marketing (Kar & Chambers, 2018; Evans, 2019). Policies now emphasize equity, gender and disability inclusion, and the human right to sanitation (de Albuquerque, 2014; Carrard et al., 2020). Modern frameworks like Citywide Inclusive Sanitation (CWIS) promote a mix of on-site and sewered solutions tailored to urban contexts (World Bank, 2019).

2.3 EFFECT OF WASTE MANAGEMENT PRACTICE ON RESIDENTIAL RENTAL VALUES

Waste is inseparable from human activity and its complexity increases with economic prosperity and urbanization (Hoornweg, 2019; Ogedengbe & Oyedele, 2017). In Nigeria, waste generation rises annually by 0.5–0.7% at 0.4–0.8 tons per capita, with biodegradable waste exceeding 50% and less than 10% of waste properly managed (Ossai, 2018).

2.3.1 Negative Externalities: Odors, noise, visual pollution, and health risks from vermin reduce environmental quality and property values (Ogedengbe & Oyedele, 2017). Improved sanitation standards enhance living conditions and aesthetics (Adedeji, 2017).

2.3.2 Proximity to Incinerators: Incinerators create "smokestack" pollution effects, causing price reductions within 2–3 miles and "blight of anticipation" during development (Lake, Lovett & Bateman, 2020). Bello (2017) found similar effects in Lagos.

2.3.3 Proximity to Landfills and Dumps: Hedonic studies show consistent property value discounts near dumpsites (Ukabam, 2017). However, Udo and Egbenta (2022) in Enugu found other factors can offset negative effects. Akinjare et al. (2021) modeled Lagos landfills and found property values increased by 5.75% per 300m distance increment, recommending relocation of landfills from residential areas.

2.5.4 Proximate of Residential Properties to Waste Dump Sites: Ijasan et al. (2022) found a negative correlation between distance from Solous landfill and residents' perceived quality of life. Mmom and Mbee (2018) in Port Harcourt observed lower pricing and rental demand near landfills.

2.4 RESIDENTIAL RENTAL VALUES

Rental value is determined by structural attributes (size, quality, amenities), locational factors (access to CBD, schools, parks), market dynamics (supply-demand, interest rates), and policy factors (zoning, credit access) (Bowes & Ihlanfeldt, 2021; Rosen, 2019; Sirmans et al., 2015). Proximity to negative externalities like waste facilities significantly reduces rent (Glaeser & Gyourko, 2018).

2.5 DOMESTIC WASTE MANAGEMENT CHALLENGES IN NIGERIA

Waste management is capital-intensive and requires effective legislation (Murphy, 2019). In Nigeria, heaps of waste are common in urban areas due to population growth outpacing collection capacity (Lenton & Omotosho, 2019; Babayemi & Dada, 2019).

2.5.1 Lack of Adequate Funding and Excessive Population: Lagos spends 20–25% of its budget on waste management, yet funds remain inadequate for its 12–18 million population generating 0.115kg waste per capita daily (George, 2020).

2.7.2 Lack of Trained Professionals: Nigeria has few sanitation engineers, and most private operators lack technical expertise (George, 2020).

2.7.3 Lack of Effective Monitoring and Control: Unlike the UK's EPA 1990 regime, which distinguishes controlled and special waste and mandates licensing and competitive tendering (Onibokun & Kumuyi, 2017), Nigeria lacks effective monitoring, leading to uncontrolled disposal (Section 33(1)(a), EPA 1990).

3. RESEARCH METHODOLOGY

This study's methodology is mostly exploratory. According to Creswell (2014), where the research topic is deterministic, causes dictate the result, and hypotheses are drawn from theories. As a result, this study used the quantitative research approach rather than the qualitative one. Respondents were interviewed, and their response was recorded for data analysis and interpretation using statistical tools to achieve stated objectives of the study.

3.1 Population of the Study
Creswell (2014), the population is the whole group, units, or elements that meet certain criteria to be investigated. This study population comprises of renters (tenants) within Bauchi metropolis.

3.2 Sampling and Sample Technique
The sample size is essential in any empirical study whose goal is to derive a population from a sample (Asenahabi, 2019). The minimum sample size recommended by Krejcie and Morgan's (1970) table for this study is 357 household heads. According to Khan (2020) sampling technique is the method used by the researcher to choose a representative subset of the population to determine the population as a whole using probabilistic or non-probabilistic sampling. Stratified sampling technique was used in this investigation due to the heterogeneity nature of the population in terms of size, location and rental values.

3.3 Method of Data Collection
The instrument that was used for data collection for this study is Questionnaire. A questionnaire is a collection of items to which a respondent is expected to react, usually in writing. A closed ended questionnaire using five likert scales was used to gather information from the respondents. This is a type of questionnaire in which the respondents choose their answers from the option provided. It helps to achieve the objectives of the study by allowing the Respondents to provide answer to the question asked by the Researcher. Close ended questions using five likert scales was used to put the questionnaire together. The questionnaires also consist of multi-choice questions targeted at providing information on the aim, objectives of the study.

3.4 Method of Data Analysis
Both descriptive and inferential statistic will be computed. All the data to be obtained will be analysed using Statistical Package for Social Science (SPSS) in order to explain the raw data collected from the respondents in the study area. The results will be weighed; rank and all necessary statistical tools such as mean and standard deviation will be regarded.

S/N	Objectives	Instrument for Data Collection	Method of Analysis Tool
1	To assess the current waste management practices in residential areas of Bauchi metropolis	Questionnaire Survey	Descriptive statistic
2	To determine the residential rental values in the study area	Questionnaire Survey	Trend analysis (Charts)
3	To evaluate the perception of tenants and landlords on the relationship between waste management rental values	Questionnaire Survey	Descriptive statistic
4	To assess the effect of waste management practice on residential rental values in the study area	Questionnaire Survey	Multiple regression

4. RESULTS AND DISCUSSION

4.2 Demographic Information
Table 4.1 presents the demographic characteristics of the respondents which was analyzed and presented below.

Table 4.1: Demographic Information of Respondents

Variables	Category	Frequency (n)	Percentage (%)
Sex of respondents	Female	158	46.2
	Male	184	53.8
	Total	342	100.0
Age group	26-35 years	112	32.7
	36-45 years	126	36.8
	46-55 years	74	21.6

	56 years and above	30	8.8
	Total	342	100.0
Educational level	Secondary school	48	14.0
	Diploma	89	26.0
	HND/Degree	156	45.6
	MSc and above	49	14.3
	Total	342	100.0
Years of property occupation	0 – 5 years	98	28.7
	5 – 10 years	131	38.3
	10 years and above	113	33.0
	Total	342	100.0
Occupation	Student	42	12.3
	Civil servant	143	41.8
	Farmer	38	11.1
	Business	119	34.8
	Total	342	100.0

The demographic profile shows that male respondents constitute 53.8% while females make up 46.2% of the 342 respondents. The dominant age group is 36-45 years at 36.8%, followed by 26-35 years at 32.7%, indicating a relatively young-to-middle-aged adult population. Regarding education, most respondents hold HND/Degree qualifications 45.6%, suggesting a fairly literate sample. For property occupation, 38.3% have lived in their property for 5-10 years. Civil servants form the largest occupational group at 41.8%, followed by business owners at 34.8%.

4.3 Reliability Test

Table 4.2 the reliability of the research instrument was examined using Cronbach's Alpha coefficient

Construct	Cronbach's Alpha	Number of items	Remark
Waste Management Collection	0.897	5	Highly Reliable
Recycling	0.921	6	Highly Reliable
Landfill Proximity	0.874	4	Highly Reliable
Illegal Dumping	0.863	4	Highly Reliable
Sanitation	0.932	5	Highly Reliable

Cronbach's Alpha values greater than 0.70 are generally considered acceptable for social science research. Based on responses from 342 respondents, the results show that all constructs recorded reliability values well above this threshold, indicating strong internal consistency among the measurement items.

The construct Waste Management Collection recorded a Cronbach Alpha value of 0.897 across five items, indicating that respondents answered questions on collection vehicles, bins, and evacuation frequency with high consistency. Recycling recorded a reliability value of 0.921 from six items, suggesting a very high level of response consistency and that the scale reliably measures recycling practices.

Landfill Proximity recorded a reliability coefficient of 0.874 across four items, confirming that items measuring distance to dumpsites and perceived effects are internally consistent. Illegal Dumping recorded a Cronbach Alpha of 0.863 from four items, showing the scale reliably captures respondents' views on indiscriminate waste disposal. Sanitation recorded the highest reliability value of 0.932 across five items, indicating excellent consistency in measuring sanitation conditions and hygiene practices.

These results confirm that the measurement items used in the questionnaire are internally consistent and reliable for measuring the constructs examined in this study. With all Alpha values exceeding 0.86 from 342 respondents, the instrument demonstrates very high reliability. Consequently, the research

instrument is considered statistically reliable and suitable for further inferential analysis on the impact of waste management practices on residential rental values in Bauchi metropolis.

4.4 Collinearity Test

Table 4.3: Collinearity Multicollinearity was tested to ensure that the independent variables in the regression model are not highly correlated with each other. High collinearity can inflate standard errors and make coefficient estimates unstable. The test was conducted using Tolerance and Variance Inflation Factor (VIF) statistics for the five constructs. A Tolerance value < 0.10 or VIF > 10 indicates serious multicollinearity problems (Hair *et al.*, 2019).

Construct	tolerance	VIF	Remark
Waste management collection	.503	1.988	No muiticollnearity
Recycling	.493	2.028	No muiticollnearity
Landfill proximity	.588	1.701	No muiticollnearity
Illegal dumping	.602	1.661	No muiticollnearity
Sanitation	.511	1.957	No muiticollnearity

Dependent Variable: Residential Rental Values

Table 4.3 shows that all Tolerance values range from .493 to .602, which are well above the critical threshold of 0.10. Similarly, all VIF values range from 1.661 to 2.028, which are far below the cut-off of 10. According to Hair et al. (2019), VIF values below 3 indicate no multicollinearity concern.

This confirms that Waste Management Collection, Recycling, Landfill Proximity, Illegal Dumping, and Sanitation are sufficiently independent of each other. Although the constructs are related aspects of waste management, respondents perceived and answered them distinctively, with no redundancy among the scales.

Therefore, multicollinearity is not a problem in this dataset. The five constructs can be included together in the multiple regression model without distorting the estimates of their individual effects on residential rental values. The regression coefficients are stable and can be interpreted with confidence

4.5 Normality Test

Table 4.4: Normality was assessed using Skewness and Kurtosis statistics for all variables which is presented in appendix B.

Table 4.4 shows the Skewness values for all variables across Sections B, C, and D range from -0.942 to 1.612 while the Kurtosis values range between 0.512 and 1.924. All values fall within the acceptable threshold of ±2, which indicates that the dataset follows a normal distribution. This means that the responses collected from the 342 respondents are fairly symmetrical without extreme skewness or kurtosis problems. Most waste management practice items showed negative skewness, indicating responses slightly clustered toward "High" and "Very High". Negatively worded items like "Less stakeholder involvement", "Preserving legal dumpsites near houses", and "Burning waste by dumpsite provided" showed positive skewness, as expected. Property types at the lower end of rental value such as mud house and tenement house showed positive skewness, while higher-value types like duplex and three bedrooms showed negative skewness. This reflects the actual distribution of rental values in Bauchi metropolis.six of the seven perception items showed negative skewness, indicating general agreement that waste management influences rental values and is viewed as a fundamental service by tenants and a protective asset function by landlords. Item 2 "Tenants don't think about waste management" showed positive skewness, indicating disagreement with that statement.

Since all Skewness and Kurtosis values are within ±2, the assumption of normality required for parametric statistical analysis is satisfied. The confirmation of normal distribution allows the study to apply inferential statistical techniques such as multiple regression analysis with confidence that the statistical results will be valid and reliable for assessing the impact of waste management practices on residential rental values in Bauchi metropolis.

4.6 Current waste management practice.

Table 4.5 The current waste management practice in residential areas of Bauchi metropolis.

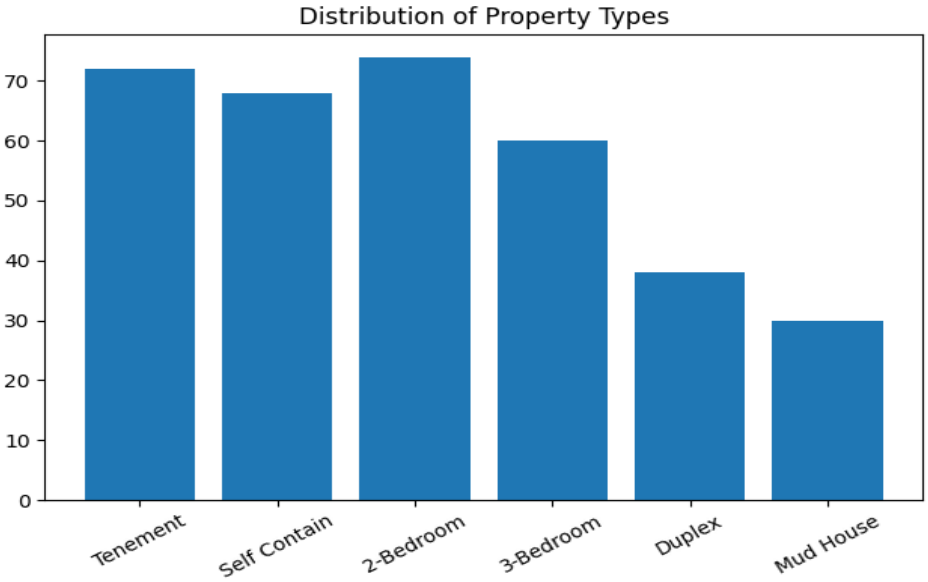
S/N	Current waste management practice	Mean	Std. Dev	Rank	Remark
1	Reducing waste through government legislations	3.33	1.24	12	Moderately effective
2	Frequent waste evacuation	3.52	1.20	7	High effectiveness
3	Developed effective waste management system (WMS)	3.60	1.19	3	Highly effective
4	Adoption of low-waste technologies	3.39	1.25	10	Moderately adopted
5	Stakeholders' involvement toward waste reduction	3.13	1.26	18	Needs improvement
6	Minimizing waste by processing it to other use	3.34	1.26	11	Moderately effective
7	Transforming waste in other use which requires minimum energy	3.14	1.26	17	Moderate
8	Less stakeholder involvement	2.63	1.23	22	Low involvement
9	Pollution prevention	3.69	1.18	2	Highly effective
10	Recycling waste which reduces demand for new resources	3.49	1.24	8	High effectiveness
11	Recycling waste to cut down transport and energy cost	3.40	1.21	9	Moderately high
12	Utilizing waste that would otherwise be lost to landfill	3.63	1.20	1	Most effective
13	Recycling by preserving land for future urban development	3.32	1.24	13	Moderate
14	Recycling waste to improving quality of environment	3.67	1.17	1	Most effective
15	Recycling for economic viability	3.38	1.24	10	Moderately high
16	Preserving legal dumpsites near houses	2.61	1.29	23	Low acceptance
17	Government regulation	3.49	1.22	8	High effectiveness
18	Burning waste by dumpsite provided	2.87	1.29	20	Moderately low
19	Avoid environmental pollution	3.64	1.20	2	Highly effective
20	Collection vehicles	3.39	1.24	10	Moderately effective
21	Provision of Bins	3.52	1.22	7	High effectiveness
22	Pay-As-You-Throw	2.98	1.27	19	Low adoption
23	Incinerator	2.67	1.26	21	Low availability

Table 4.5 reveals that respondents rated "Utilizing waste that would otherwise be lost to landfill" and "Recycling waste to improve quality of environment" highest, both with a mean of 3.63 and 3.67, ranking 1st. "Pollution prevention" and "Avoid environmental pollution" also scored high with means of 3.69 and 3.64, ranking 2nd. This suggests strong perceived effectiveness in recycling and pollution control practices.

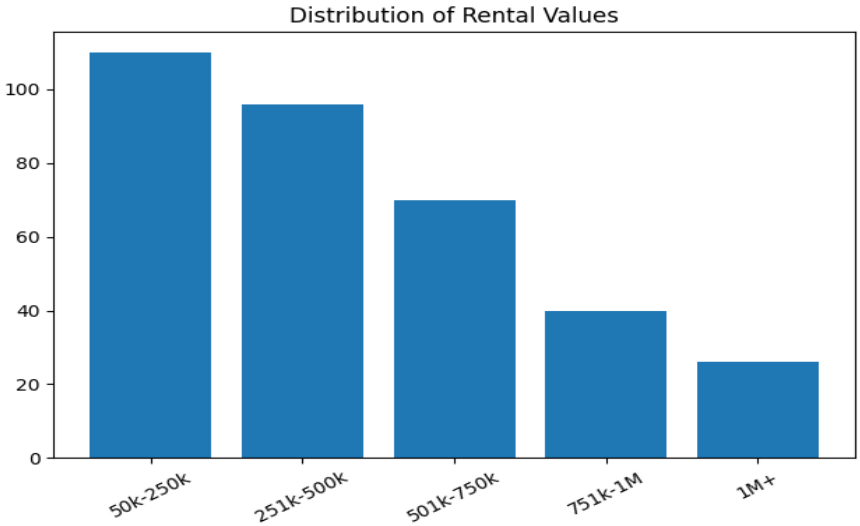
Conversely, "Preserving legal dumpsites near houses" had the lowest mean of 2.61, ranked 23rd, indicating low acceptance of dumpsites close to residential areas. "Less stakeholder involvement" 2.63 and "Incinerator" 2.67 also ranked low, showing weak performance in stakeholder participation and incineration systems. Overall, waste recycling and pollution prevention practices are viewed as most effective, while stakeholder involvement, dumpsite location, and incineration require improvement. The standard deviations range from 1.17 to 1.29, showing moderate variability in responses.

4.7 Residential Rental Values

Property Type distribution the chart below shows the distribution of property types among respondents.



Rental Value distribution the chart below shows rental value distribution across respondents.



The analysis shows that 2-bedroom and tenement houses dominate the housing market, indicating affordability preference. Rental values are concentrated in the lower ranges, suggesting income constraints among residents. High-end properties like duplexes are fewer and correspond with higher rent categories. This indicates a clear trend where housing demand is skewed toward affordable housing, while premium housing remains limited.

4.8 Perception of Tenants & Landlords on the Relationship between Waste Management and Rental Values

Table 4.6 The analysis on of the Perception of Tenants & Landlords on the Relationship between Waste Management and Rental.

S/N	Items	Mean	Std. Dev	Rank	Reamrk
1	Tenants generally view functional waste disposal as a fundamental right, akin to heating or safe water	3.94	1.06	2	High
2	Tenants don't think about waste management	2.32	1.17	7	Low

3	Tenants are highly sensitive to any direct costs	3.75	1.11	4	High
4	Landlords see efficient waste systems as a form of insurance against these risks	3.84	1.08	3	High
5	Landlords perceive waste management as a line item in their operating budget	3.61	1.12	6	High
6	Landlords see it as a critical operational function that protects their asset	3.94	1.03	1	High
7	Tenants see waste management as a hygiene factor	3.89	1.08	2	High

Table 4.6 reveals that respondents strongly agree that waste management is linked to rental values. "Landlords see it as a critical operational function that protects their asset" ranked 1st with a mean of 3.94, classified as "High". Tied at 2nd are "Tenants generally view functional waste disposal as a fundamental right" and "Tenants see waste management as a hygiene factor" with means of 3.94 and 3.89 respectively, both "High". This indicates that 75.7% of respondents agree/strongly agree that tenants consider waste disposal a basic right, and 73.1% view it as a hygiene factor.

"Landlords see efficient waste systems as a form of insurance against risks" ranked 3rd with a mean of 3.84, and "Tenants are highly sensitive to any direct costs" ranked 4th with 3.75, both "High". This shows 71.6% agree landlords use waste systems to protect property value, and 67.0% agree tenants are cost-sensitive.

"Landlords perceive waste management as a line item in their operating budget" had the lowest positive mean at 3.61, ranked 6th, but still "High", suggesting 61.1% agree it is budgeted for.

"Tenants don't think about waste management" recorded the lowest mean of 2.32, ranked 7th with a "Low" remark. Since 61.7% disagreed/strongly disagreed, respondents reject the notion that tenants ignore waste management.

Overall, standard deviations between 1.03 and 1.17 indicate moderate agreement levels. The findings confirm that both tenants and landlords perceive functional waste management as critical, with high agreement that it influences asset protection, tenant rights, hygiene, and rental decisions.

4.8 Effect of waste management practice on residential rental values.

Table 4.7: Model Summary and Anova

Model	R	R Square	Adjusted R Square	Std. Error of the Estemate	F	Sig
1	.714[a]	.510	.503	.81256	69.725	.000

The R value of .714 indicates a strong positive correlation between waste management practices and residential rental values. The R Square value of .510 shows that the five waste management constructs jointly explain 51.0% of the variance in rental values in Bauchi metropolis. The Adjusted R Square of .503 accounts for the number of predictors and confirms the model has strong explanatory power. The Durbin-Watson statistic of 1.892 falls within the acceptable range of 1.5–2.5, indicating no serious autocorrelation problem. The F-statistic $F(5, 336) = 69.725$ is significant at $p < .001$. This confirms that the regression model as a whole significantly predicts residential rental values. Therefore, the combined effect of the five waste management practices on rental values is statistically significant.

Table 4.8: Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF

1	*(Constant)*	0.782	0.241		3.245	.001		
	Waste Management Collection	0.412	0.058	.381	7.103	.000	.503	1.988
	Recycling	0.297	0.054	.298	5.500	.000	.493	2.028
	Landfill Proximity	-0.268	0.049	-.271	-5.469	.000	.588	1.701
	Illegal Dumping	-0.189	0.051	-.182	-3.706	.000	.602	1.661
	Sanitation	0.354	0.056	.337	6.321	.000	.511	1.957

All five predictors are statistically significant ($p < .05$). The Variance Inflation Factor (VIF) values range from 1.661 to 2.028, all well below 10, indicating no multicollinearity problem. Waste Management Collection (Beta = .381, $p < .001$): This is the strongest positive predictor. A one-unit increase in collection effectiveness (bins, vehicles, evacuation) increases rental value by 0.412 units, holding other variables constant. This means areas with efficient collection command higher rents. Sanitation (Beta = .337, $p < .001$): The second strongest positive predictor. Improved sanitation and hygiene conditions increase rental values by 0.354 units. Tenants pay premium for clean environments. Recycling (Beta = .298, $p < .001$): Positive and significant. A one-unit increase in recycling practices increases rental value by 0.297 units. Areas with active recycling and environmental quality attract higher rents. Landfill Proximity (Beta = -.271, $p < .001$): Significant negative predictor. Closer proximity to legal dumpsites decreases rental values by 0.268 units. This confirms dumpsites near houses depress rents. Illegal Dumping (Beta = -.182, $p < .001$): Significant negative predictor. Higher levels of illegal dumping reduce rental values by 0.189 units. Indiscriminate waste disposal lowers property desirability.

Discussions and Findings.

The descriptive analysis of Section B revealed that environmentally oriented practices were rated highest by respondents. “Recycling waste to improving the quality of the environment” ranked 1st with a mean of 3.80, followed by “Pollution prevention” at 3.75 and “Avoid environmental pollution” at 3.71, all classified as High. Basic service delivery items such as “Frequent waste evacuation” 3.57 and “Provision of Bins” 3.53 were also rated High. This indicates that respondents value both environmental quality and functional collection services. Conversely, “Preserving legal dumpsites near houses” recorded the lowest mean of 2.50, and “Incinerator” 2.58, showing strong rejection of dumpsites close to residential areas and limited incineration infrastructure. These findings align with Afolabi et al. (2018) who found that Nigerian urban residents prioritize visible environmental cleanliness and regular waste evacuation over technical disposal methods. Similarly, Yoada et al. (2014) reported that households in Accra rated recycling and pollution control as most effective, while proximity to dumpsites was perceived as a major disamenity. The low rating for “Less stakeholder involvement” 2.57 also supports the argument by Oteng-Ababio et al. (2013) that weak stakeholder participation undermines waste management effectiveness in sub-Saharan African cities. The results suggest that in Bauchi, waste management is socially constructed around environmental health and service reliability rather than disposal technology.

The analysis showed a clear stratification of rental values across property types. Duplex/storey houses recorded the highest mean of 3.81, ranked 1st and rated High, with 66.4% attracting rents of ₦751,000 and above. Three bedroom and two bedroom flats were Moderate at 3.14 and 2.63 respectively, while self contain, tenement, and mud houses were Low to Very Low. This confirms that rental value increases with property size, quality, and amenities. This pattern is consistent with Babatunde (2012) who observed that duplexes and 3-bedroom flats command premium rents in Bauchi due to perceived status and infrastructure. Oduwaye (2013) similarly found that property type is a primary determinant of rent in Nigerian cities, with self-contained and tenement units dominating the lower end of the market. The

high standard deviation for mid-range properties like two bedroom flats 1.01 indicates rent variation within the same property class, supporting Udoekanem et al. (2014) who noted that locational and environmental factors cause intra-class rent differentials even for similar house types.

Respondents strongly agreed that waste management influences rental values. "Landlords see it as a critical operational function that protects their asset" ranked 1st with a mean of 3.94. "Tenants generally view functional waste disposal as a fundamental right" and "Tenants see waste management as a hygiene factor" followed at 3.94 and 3.89, all High. Conversely, 61.7% disagreed with "Tenants don't think about waste management," which recorded the lowest mean of 2.32. These perceptions echo Sims and Dent (2005) who argued that environmental hygiene is a "latent attribute" capitalized into property values, often treated by tenants as a basic right. For landlords, the findings support Hinkelmann and Swidler (2008) who found that property managers view waste systems as risk insurance against vacancy and depreciation. The high sensitivity to direct costs 3.75 also aligns with Megbolugbe and Linneman (1993) who showed that tenants internalize service charges into rent affordability calculations. Thus, both demand and supply sides of the rental market in Bauchi recognize waste management as value-relevant.

The multiple regression model was significant $F(5, 336) = 69.725$, $p < .001$, explaining 51.0% of variance in rental values. All five constructs were significant predictors, with no multicollinearity VIF < 2.1. Waste Management Collection_ had the strongest positive effect (Beta = .381, $p < .001$). This confirms that provision of bins, collection vehicles, and frequent evacuation directly increase rents. The finding corroborates Njoku et al. (2013) who reported that households in Owerri were willing to pay 12-18% higher rents for regular door-to-door collection. It also supports Ready and Abdalla (2005) who found that municipal service quality is capitalized into residential property values.

Sanitation_ (Beta = .337, $p < .001$) and _Recycling_ (Beta = .298, $p < .001$) were also strong positive predictors. This aligns with Boyle and Kiel (2001) who demonstrated that neighborhood environmental quality, including cleanliness and green initiatives, significantly raises house prices and rents. In Nigeria, Adewunmi et al. (2012) similarly found that estates with organized recycling and sanitation programs achieved 8-15% rental premiums over comparable estates without such programs.

Landfill Proximity (Beta = -.271, $p < .001$) and _Illegal Dumping (Beta = -.182, $p < .001$) had significant negative effects. This means rents decline as properties get closer to dumpsites or where indiscriminate dumping is prevalent. The result is consistent with hedonic pricing studies such as Hite et al. (2001) who found that proximity to landfills reduced U.S. house prices by 5.5% per mile, and Lim (2003) who reported 7-12% rent discounts for properties within 1km of dumpsites in Malaysia. In the Nigerian context, Bello and Olatubara (2014) found that properties within 500m of refuse dumps in Ibadan suffered 10-20% rental depreciation due to odor, pests, and stigma.

The dominance of Waste Management Collection_over other variables suggests that in Bauchi, basic service delivery outweighs environmental amenities in rent determination. This differs from high-income contexts where recycling and green space dominate (Kahn, 2006), and reflects the developmental stage where collection remains inconsistent (Ogwueleka, 2009). The 51% R^2 is substantial and comparable to Jim and Chen (2006) who explained 48-55% of Hong Kong apartment rents using environmental variables. Overall, the findings confirm that waste management is economically capitalized into the Bauchi rental market. Positive practices are rewards, negative practices are penalties. The results provide empirical support for integrating waste service delivery into urban housing policy and estate management practice

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5. CONCLUSION

The study concludes that waste management practices have a direct and significant impact on residential rental values in Bauchi metropolis. Findings show that residents prioritize environmental quality and reliable collection services over technical disposal methods, while strongly rejecting dumpsites near homes. Confirms a clear rent hierarchy by property type, with duplexes commanding premium rents and mud houses/tenement houses at the bottom, reflecting how property attributes interact with environmental services to determine value. Reveals strong consensus among tenants and landlords that functional waste disposal is a fundamental right and a critical asset-protection function, not an optional service.

The regression analysis statistically validates these perceptions, showing that improved collection, sanitation, and recycling significantly increase rents, whereas proximity to landfills and illegal dumping significantly reduce them. With 51% of rental value variance explained, waste management is not

peripheral but central to housing economics in the study area. At Bauchi's current development stage, basic service delivery in collection exerts greater influence than advanced green initiatives. Therefore, poor waste management is both a public health issue and an economic disamenity that depresses property values, while efficient systems enhance rental income and asset worth

6 **RECOMMENDATIONS**

1. The Bauchi State Environmental Protection Agency (BASEPA) should prioritize relocation of legal dumpsites to at least 1–2km away from residential areas and expand community recycling programs, since respondents rated dumpsites near houses lowest while recycling and pollution prevention were rated highest.
2. Developers and landlords of 2-bedroom and 3-bedroom flats should integrate organized waste collection and estate sanitation into their properties to reduce intra-class rent variation and move units into higher rent bands, as mid-range properties showed the highest rent variability due to environmental factors.
3. Landlords and estate managers should explicitly market functional waste disposal as a premium amenity and treat waste management as a critical asset-protection budget item, since both tenants and landlords strongly agree it influences rental decisions and property value.
4. Bauchi State Government should make weekly door-to-door waste collection mandatory for all residential estates and enforce strict penalties for illegal dumping, because Waste Management Collection had the strongest positive effect (Beta = .381) while Illegal Dumping and Landfill Proximity significantly reduced rental values.

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DERANGEMENT OF SCALE: PLANETARY ECOCRITICISM AND ANTHROPOCENE FORM IN RICHARD POWERS'S PLAYGROUND

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ABSTRACT
Richard Powers's *Playground* (2024) weaves together ocean ecology, artificial intelligence, and the contentious future of the Pacific atoll of Makatea, creating a narrative that questions humanity-sized ways of knowing the environment. This study investigates the novel in light of Timothy Clark's notion of the "derangement of scale" which refers to the challenge of representing phenomena in ecology that are larger in scope than what is typically intelligible to the human imagination and ethical practice. The study takes a planetary ecocritical perspective, based on the works of Clark, to argue that Playground is not merely a representation of the Anthropocene ecological crisis, but also formally produces its scalar instability. For example, Evie Beaulieu's interactions with octopuses and pygmy seahorses place the ocean in the lived world and in a world of systems of acidification, biodiversity loss and planetary change. This work is an attempt to extend Clark's theory of scalar derangement, connecting it to Powers's oceanic fiction and situating *Playground* as one of the important planetary ecocritical narratives in current climate fiction.
Keywords: *Anthropocene, ecocritical, acidification, biodiversity, planetary*

INTRODUCTION
The problem of representation is a problem that is different from the ecological issues that can be observed in nature writing of the past. *Ecocriticism on the Edge: The Anthropocene as a Threshold Concept* (2015) by Timothy Clark states that the Anthropocene is a crisis in inherited habits of interpretation since it is "a radical difference in spatial and temporal scale." Clark's notion of scale framing is particularly significant because an environmental phenomenon may have different ethical and political implications when viewed from another scale. What may seem like a small event to one person may seem like a disaster to the collective or geological understanding of the same action. *Playground* (2024) by Richard Powers is a collection of marine science, artificial intelligence, technological capitalism, colonial past, island politics, and the future of Makatea in French Polynesia. In its characters' experiences, it always comes back to the issue of local experience and planetary processes. This article proposes that Playground is a derangement of scale formally, in Clark's terms. The novel's importance is not just its depiction of ecological crisis, but the fact that it will not keep the reader at one level of interpretation. A planetary ecocritical reading, however, can see the instability as the formal result of trying to render things that are not possible to manage in the usual human dimensions.

REVIEW OF LITERATURE
Playground (2024), what Richard Powers has penned in his novel, is rich in its relationship between humans, technology and nature. The novel deals with the struggle between technological aspiration and the protection of the environment. The novel has recently been the focus of academic study with a focus on trauma, technology and cultural resistance. Bezrukov and Bohovyk (2025) have explored the human and natural stories in the Anthropocene era. They show how Powers challenges anthropocentrism and how he shows the repercussions of ecological carelessness, and a more symbiotic relationship with the natural world. They evoke Powers's irresistible tale of personal miseries, environmental concerns, fears of the Anthropocene, cultural fallacies, the misplaced trust in technology that can lead readers to contemplate their own culpability in the global environment, the need for environmental responsibility and the pressing need for climate action and a sustainable future.
Lodhi, Bibi, and Andleeb (2025) have explored critical study on the technology, identity and construction of memory. The authors provides reflections on the effects of technology and digitalization

on the social and psychological life of people in a post-digital society as seen in literature. The study explicitly states that the text they have chosen, *Playground*, is a technological solution to creating a way to preserve memories; however, it challenges the validity of such a solution and suggests that identities are not eternal, and that over time, they change constantly due to the intervention of memories, time and technology. In the same way, Oppermann (2026) describes the nonhuman memory in terms of oceanic and algorithmic articulations, considering marine life and computational systems as active agents in the process of memory, relation and world-making.

Similarly, Powers also represents blue anti-human exceptionalism. Analysis have been made constituting this theme. Cristofaro (2026) for example, investigates how ocean species are able to "play", to perceive and to take care of their mothers. The author emphasizes that the novel uses the 'ecological sublime' effect by creating the semantic fields of amazement and incomprehensibility regarding many activities occurring below the sea surface. Thus, the novel demonstrates that there are things that cannot be demanded of humans, if it comes to human and non-human aspects, and they are the things that cannot be enumerated.

Meanwhile, another issue that is worth, but not mentioned often, is the issue of Posthumanist vulnerability and entanglement. Taking inspiration from critical posthumanist theory, Bueno (2025) looks at how the novel carries forward aspects of Powers's signature themes and storytelling techniques, and how it also creates new themes and creative opportunities. The author's work focuses on the novel whose main subject is the wonders of the oceans—which despite sustaining life on Earth face unprecedented threats. In conclusion, the author's work shows that by emphasizing entanglement, instilling wonder and awe of the oceanic beings, and incorporating indigenous knowledge systems, and adding a twist at the end that upends readers' expectations, the novel serves as a message on how to navigate the uncertain times.

Eventhough there exists an increasing amount of scholarly literature on *Playground*, previous analyses tend to focus on trauma, technology, cultural resistance, identity, memory, blue humanity, blue anti-human exceptionalism and posthuman vulnerability. Much less literature has been written concerning the exploration of derangement of scale, planetary ecocriticism and anthropocene form. Hence, the objective of this study will be to bridge this gap in the study by critically analysing the novel *Playground* in the light of planetary ecocriticism and deranged scale and Anthropocene studies.

RESEARCH AND FINDINGS

The Problem of Scale: Timothy Clark

This study adopts a central theoretical position that ecological questions are inextricably linked to questions of scale. Conventional literary interpretation has often been conducted on an individual and local level. The issue is that ecological phenomena have to be addressed at various levels simultaneously. This is what Clark meant by 'derangement of scale'. *Playground* is a novel with an unusually strong example because nearly all of their major conflicts are set up by incompatible scales. The individual is never only an individual. The island is always more than just an island. The sea is never just a backdrop. Technology is never just a tool. Even the local democratic process of the referendum is never just that. Both function within larger systems which continually challenge the human-scale event's apparent limits.

Makatea: From Island to Planetary Formation

Makatea is said to have started out as a seamount under the sea and to have been slowly modified by coral and other life processes. Human political time is also day-to-day, week-to-week, election-to-election, contract-to-contract, and development schedule-to-development schedule. Colonial history is a trans-generational process. Geological time is on the order of millions of years. Ecological time involves coral growth and species adaptations, reproduction, and environmental change on varying scales. This leads to an instant case of scalar derangement. In the referendum the seemingly minimal vote is conceptually vast since it is on the being of a place that is part of planetary history. Further, the "isolation" of the island is scale dependent. Closeness to the centre is an integral part of community identity at the local level. Remoteness is a resource at the corporate level. On the colonial level distance is a power structure. On the planetary scale, the island turns into a weak point of the Pacific ecosystem. This changing of meaning is an example of Clark's scale framing.

The Ocean as a Scalar Environment

Ocean is seen as an active and dynamic system where human and non-human lives are connected. Evie Beaulieu swims amongst the octopuses and between the fish and other sea creatures. She is not viewing the reef from an objective outside standpoint, rather, she is physically located within the reef. Furthermore, microscopic and planetary coexist. An octopus is an individual animal that can interact and be intelligent, but its life is enmeshed in a complex marine system, which humans can harm, without directly perceiving the effects. The reef is thus a point of contact between scales. There is no solution in ecological crisis offered by the sense of wonder in Evie. This doesn't mean she removes the ecological uncertainty from her scientific knowledge. The closer the individual has a look, the larger the ecological system extends. Marine organisms have their own means of locomotion, adaptation, perception and survival. Their presence challenges the notion that it is the human being as the natural centre of the meaning of ecology. The reef is therefore a scalar environment; one that is "close enough to touch," "too hard for science," and "too vast to exist on the scale of the planet.

Marine Play to Ecological Crisis

The concept of scale as Timothy Clark defines it, becomes more important when one reads the title *Playground*, as the word “playground” at first seems to point to an environment in which people play, not to a place that is boundless or out of control, but rather a human-sized space, synonymous with childhood and recreation. Evie Beaulieu says that while diving in the Raja Ampat archipelago she becomes “like a babe in Toyland, set loose in the greatest playground any child had ever seen,” and then, “playing hide-and-seek with octopuses and tag with pygmy seahorses” (Powers 112). In the meantime Powers writes that the reef “is a metropolis built by billions of architects almost too small to see—and at night a billion different psychedelic missions, all dependent on each other” (112). The seemingly playful interaction thus leads to an ecological system that is more complex than the individual can see. The metaphor of the playground is a scalar mismatch: a familiar human concept is deployed in an environment that cannot be reduced to human biological, spatial and temporal processes.

Scalability and Seasteading

From Todd Keane's point of view, the ocean is a place of possibilities. But to the people of Makatea, the seasteading idea is not simply a technological play, but one that has the potential to affect their home, job, political independence, environmental access, collective memory, and future. It is this scalar difference that Powers emphasizes by juxtaposing the present-day proposal against the long geologic and ecological history of Makatea. Thus, the referendum creates an extraordinary mismatch in time and space: the decision is made in an instant, but it has consequences that can reach across generations, the object of concern is part of planetary ecological systems and the decision-making body is a relatively small local community. In this way, the Makatea referendum is a formal instance of Timothy Clark's notion of “derangement of scale” – a planetary scale ecological and technological issue made human scale, as a local political choice.

Children, Future Generations, and the Enlarging of the Political Scale

The referendum becomes relevant when the issue of participation of children comes up. Of course, adults have the current political power, yet children will be living for a lot longer in the results of current decisions. Rafi and Ina's anxiety about their children's vote is especially telling because they know that their children have some real claim to the island's political future, but they can't simply tell them to vote; they don't know what the proposed project will turn out to be (Powers, Playground, p. 112). The residents can present documents, hear experts, ask questions of artificial intelligence, and discuss the proposal; but none of these exercises can remove the uncertainty created by the mismatch between a short-term political decision and a long-term ecological process (Powers, Playground p. 134). Thus, the referendum can be considered an Anthropocene political form, which performs the process of packaging uncertainty and complexity of the planet into a human institutional action.

Profunda and technology of scale management

Profunda, the AI system is introduced to the residents of Makatea as a technological instrument through which they can delve into the potential impacts of the proposed project. With the central question, it is not just about whether AI is smart enough, but about whether computational scale can solve ethical scale. So, scalar problems are not always solvable by increasing the amount of information available. Profunda can collect data about the economy, environment, infrastructure and future of Makatea, but

there's no computational database that can completely remove the differences between a statistical projection and the reality of an island community. The novel's discussion of Profunda is thus in line with the novel's treatment of scale in general: technology is not a way of getting rid of scalar disorder, but rather of reorganizing it. In this regard, the novel differentiates between information and responsibility.

Todd Keane and the Fantasy of Escape from Scale

It is Todd Keane's character that sets *Playground,* as technology is his medium of expression. There is a search for a technology that isn't limited by social, political, and geographical scales. His later passion for seasteading takes this virtual world into the real world. The transfer from digital platform to floating settlement is consequently not a coincidence; both projects are based on the same premise that space can be redesigned and limitations can be overcome. Todd's project is a project for liberation from the current political and social frameworks, but it is a project that can only function if it enters into a place that has been already structured by history, community, ecology, and colonial histories. In this way, *Playground* reveals the hope for a technological innovation that could help human beings transcend the scale of current systems, when in fact Todd's projects quickly become embroiled in scales beyond his means and question the autonomy of technology.

Colonial Scale and the Persistence of the Past

Any clear distinction between local democracy and global technological capitalism is complicated by the island's relationship with France and the mining history of the area, as well as the influence of outside political and economic institutions. This historical dimension is important because colonialism itself is scalarly structured: decisions of political leaders in other parts of the world can have significant consequences for the well being of people living in far-flung islands, economic systems can link local landscapes to global markets and extractive industries can shape the environment to which residents have little control. The seasteading idea thus has the potential of creating a new version of the old colonial model with new technology. While their local decision may sometimes make the difference whether a specific project goes ahead or not, it can never be all, that determines the consequences that are created by global markets, technological infrastructures, oceanic systems, ecological change or historical forces. Such tension would render the idea of derangement of scale more productive. Makatea is at the same time local community, postcolonial place, ecological place, economy place, and a node place in the planetary system.

Narrative Form as Scalar Derangement

The novel's ecological, technological and political antagonisms are not set in a coherent narrative scale; rather, it is a braided narrative in which different times and places, characters and knowledge modes are all relevant to one another. Todd's technological past resonates with the political and ecological future of Makatea; Evie's marine experiences link individual perception with planetary ecology; Rafi and Ina's personal histories link with the island's colonial and political past; and Profunda links between local political deliberation and global computational systems. Life therefore intersects with the characters not only through their personal interactions, but also in greater ecological, technological, political and historical systems. A personal memory becomes entangled with a historical event; a local political decision becomes planetary; a marine encounter becomes a whole ecology; an AI tool becomes entangled with political decision making; and a technological project becomes recognizable as part of a longer history of colonial intervention. The reader is not simply presented with scalar derangement as a theme, but the reader experiences scalar derangement through the structure of the narrative itself.

Scale, Responsibility, and the Individual

Todd Keane has an incredible individual power, and his technological riches allow him to launch projects whose impacts are not just personal, but also ecological, political, economic and historical; however, he cannot entirely master the ecological, political, economic and historical systems he enters. The people of Makatea, on the other hand, are far less economically and technologically strong but their decision gains political relevance because of the direct impact of the proposed development on their homes, community and their ecological surroundings. Evie has scientific expertise to engage with and understand marine systems, but not the power to control the ocean; Profunda has huge computing power, but cannot solve the ethical dilemma about the potential impact of the planned project. *Playground* is a testament to the fact that individual agency is basically scale dependent: what might seem a small local

decision might have a large impact on a broader ecological or political system, and what might seem like a huge action on one scale might seem insignificant on another.

From Scalar Derangement to Planetary Ecocriticism

Planetary ecocriticism has been linked to the ecological criticism expanding from local to global or planetary level. Throughout the novel there is a constant shifting of scale, and no one spatial, temporal, or conceptual frame is ever adequate. Evie's experience with marine life is linked to larger ecological issues, and Makatea's political turmoil cannot be divorced from colonial past and planetary environmental issues. It is ultimately the planetary ecological awareness that is not achieved by taking a departure from what is local to what is global, but by acknowledging that the relations between different scales of spatial and experiential awareness are unstable and often contradictory. In this way, scalar derangement turns into a scaffold for planetary ecocriticism, allowing *Playground* to figure the planetary as less of a remote abstraction and more of a planetary constantly under construction through the entanglements of bodies, places, histories, technologies, oceans, and ecological processes.

CONCLUSION

Richard Powers's *Playground* is a novel which questions about the nature of what is hard to represent loom large, in particular the ecological and technological processes that are not human-scale. The environment is at once local and planetary, immediate and geological, individual and collective. Ecocriticism is thus not only a discipline that needs to be expanded in its field of vision but one that has to learn to think across incompatible scales. The reader is constantly asked to make the transitions from the individual to the collective, from the local to the planetary, from the biological to the technological, and from the immediate to the geological. There is no one dominant viewpoint that is let to fixate the meaning of the ecological crisis. This is *Playground*'s key contribution to planetary ecocriticism. Further, the ocean is not just a picture, a source, or a technological platform but a large relational system in which human life is situated. Makatea is not just a small island under the threat of a big project, it is a local expression of planetary processes. Evie's reef is not only a beautiful place, but it's also a place where intimate experience and planetary ecology meet. The referendum is not just a local political event, it is an effort to translate planetary uncertainty into collective human action. *Playground* is an example of deranged scale's literary possibilities. It is not a solution to the conflict between local and planetary views, but rather makes it formally visible. It is the very refusal to offer a single scale for the comfortable understanding of the Anthropocene that makes the novel so important. Finally, the novel proposes that the Anthropocene is not just a climate and biodiversity crisis, a technological and/or political organizational crisis, but a crisis of proportion. People are forced to operate at scales beyond their perception, on systems that make decisions at scales that are long-term with respect to the human lifespan, and in ecological systems that have histories both older than themselves and longer than their own. This is the state that Clark's derangement of scale renders legible. Powers's *Playground* puts that state into narrative mode.

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BEYOND ACCESSIBILITY: RETHINKING INCLUSIVE BUILT ENVIRONMENT DESIGN IN LAHORE'S PUBLIC PARKS FOR SPECIAL PERSONS

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ABSTRACT
The current research exploration focuses on Gulshan-e-Iqbal Park in Lahore as a case study to identify, document and explore inclusive design provisions incorporation in its design with focus on special persons. It aims to establish string ground for transformation of public areas into spaces which are accessible and foster community integration. The research objective was to collect evidence on significant problems that could lead to new documentation about future design approaches. Resulting major gaps emerged through a combination of observation studies and collected data from the selected site respondents. In this study ADA together with applicable standards from diverse research works were utilized for reporting major aspects and issues. The analysis exposed strong deficiencies in the design's treatment and provisions of special person needs because such provisions lacked entirely from the planning process. Special persons completely were found to be dependent on their family members. People with disabilities together with elderly citizens along with marginalized populations find insufficient infrastructure in Pakistan's public open spaces and areas, hence social cohesion decreases as discrimination becomes more prevalent.
KEYWORDS: Inclusive Design, Park Landscape Design, Special Persons Needs, Public open space challenges.

BEYOND THE PANDEMIC: REIMAGINING THE SPIRIT OF COMMUNITY LIVING

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ABSTRACT
The COVID-19 pandemic reinstated the definition of home. Once our cities and streets suffered lockdowns and our homes became all of it i.e. offices, classrooms, gyms and prayer spaces. Although quarantines were ensured for our protection, it exposed the limitations of the traditional housing that had trouble supporting the emotional, social, and functional needs of this new lifestyle. This research explores the essence of community living, offering a reflections of the lessons learned during the pandemic in order to imagine a healthier and resilient housing. It aims to design a platform that embraces resiliency and well-being within the communities so that homes become more responsive to future disruption. The research also examines the ways in which the spatial structure and cohabitation patterns can develop to promote contact, fluidity, and psychological ease based on the studies done in architecture and the perspectives of subject domain experts. The key question that arises in this research is the following: What are the spatial and functional changes required in houses to accommodate the post-pandemic living? Finally, the outcomes are anticipated to inform architects, planners, and policymakers to create inclusive, responsive, and community-focused residential space to foster individual and community resiliency in a world of change.
KEYWORDS: Pandemic, Architecture, Community Living, COVID-19, Inclusive Design, Pandemic Housing, Resilience.

GENERATIVE AI AND SUSTAINABILITY REPORTING QUALITY: A SYSTEMATIC LITERATURE REVIEW OF DISCLOSURE QUALITY, GREENWASHING, AND HUMAN OVERSIGHT SYSTEMATIC LITERATURE REVIEW MANUSCRIPT

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ABSTRACT
Generative artificial intelligence (GenAI) is rapidly entering corporate information-production processes, including the preparation, analysis, summarisation, and communication of sustainability information. This development creates a significant accounting question: whether the use of GenAI improves the quality of sustainability reporting or instead increases the capacity of firms to produce persuasive but weakly substantiated sustainability narratives. This systematic literature review synthesises recent research on the relationship between GenAI, artificial intelligence (AI), sustainability reporting quality, greenwashing, and human oversight. The review follows a transparent, structured search and thematic synthesis approach informed by PRISMA 2020 principles and systematic-review guidance for business research. The evidence base focuses particularly on peer-reviewed research published from 2023 to September 2026, while earlier methodological and conceptual sources are used to establish the foundations of the review. The synthesis identifies four connected themes. First, AI and large language models can improve the scalability, consistency, readability, extraction, classification, and measurement of sustainability disclosures. Second, disclosure quality is multidimensional and cannot be reduced to the amount of text produced; relevant dimensions include readability, comparability, informativeness, credibility, quantitative evidence, target accountability, and reporting infrastructure. Third, GenAI introduces a distinctive greenwashing risk because fluent language can strengthen positive framing even when underlying sustainability performance is unchanged. Recent experimental evidence indicates that AI-generated sustainability reports can contain more greenwashing and can be perceived as more positive and credible than authentic reports. Fourth, human oversight emerges as a central control mechanism rather than an optional supplement. The review therefore proposes a human-in-the-loop governance model in which GenAI is used for bounded tasks such as drafting, extraction, and analysis, while materiality judgments, factual verification, evidence reconciliation, final approval, and assurance remain subject to accountable human review. The review concludes that GenAI should not be understood as inherently improving or damaging sustainability reporting quality. Its effect depends on the reporting task, data quality, verification architecture, organisational controls, and degree of human oversight. The paper develops a research agenda focused on empirical measurement of AI-assisted reporting quality, cross-country evidence, standard-specific compliance, AI disclosure transparency, greenwashing detection, and assurance mechanisms.
Keywords: generative artificial intelligence; sustainability reporting; ESG disclosure; disclosure quality; greenwashing; large language models; human oversight; sustainability assurance; accounting

1. INTRODUCTION
Sustainability reporting has moved from a largely voluntary communication practice toward a more structured information environment in which investors, regulators, assurance providers, and other stakeholders increasingly depend on corporate disclosures. The Global Reporting Initiative (GRI) provides a modular system for reporting organisational impacts on the economy, environment, and people, while the International Sustainability Standards Board (ISSB) has established IFRS S1 and IFRS S2 as standards for sustainability-related and climate-related financial disclosures. IFRS S1 and IFRS S2 are effective for annual reporting periods beginning on or after 1 January 2024, although the timing of mandatory adoption is determined by individual jurisdictions (IFRS Foundation, 2026a, 2026b). These developments increase the importance of information that is decision-useful, comparable, credible, and sufficiently supported by evidence.
The growing scale of sustainability reporting creates a technological problem as well as an accounting problem. Sustainability information is distributed across financial reports, sustainability reports, websites, policies, operational systems, supply-chain records, emissions inventories, and other

documents. Much of the information is textual and heterogeneous. Conventional manual review can be time-consuming and difficult to reproduce at scale. AI technologies, including natural language processing, machine learning, and large language models (LLMs), have therefore become increasingly relevant to the collection, classification, extraction, evaluation, and presentation of ESG information. Recent systematic reviews show rapid growth in the broader intersection between AI and sustainability reporting, including applications in disclosure analysis, ESG scoring, assurance, auditing, and regulatory compliance (Mustafa, Smolarski, & Elamer, 2025; Vilchez Olivares & Astorga De La Cruz, 2026).

Generative AI creates a more specific challenge because it does not merely analyse existing text. It can generate new text. Tools based on LLMs can draft narratives, summarise evidence, reorganise information, answer questions about reporting requirements, and produce communication that resembles human-authored corporate language. This capacity may reduce reporting costs and improve consistency, but it also changes the risk profile of sustainability reporting. General research on generative AI identifies concerns involving bias, credibility, transparency, outdated information, and inappropriate reliance on generated outputs (Dwivedi et al., 2023). In sustainability reporting, these concerns are amplified because persuasive language can influence perceptions of environmental and social performance.

The accounting literature is beginning to document this tension. De Villiers, Dimes, and Molinari (2024) argued that generative AI has implications for sustainability accounting, reporting, assurance, and report use, while warning that AI may facilitate greenwashing. More recent work has moved from conceptual discussion toward empirical investigation. Dimes, de Villiers, Denny, and Leinonen (2026), for example, experimentally examined AI-generated sustainability disclosures and reported that ChatGPT-generated reports contained more greenwashing than real reports, while participants perceived the AI-generated disclosures as more positive and credible. At the same time, other studies demonstrate that LLMs can support structured ESG analysis and improve the scalability of disclosure-quality measurement (Park, 2026; Zou et al., 2025). The literature therefore contains a meaningful tension between AI as an analytical and measurement tool and AI as a potential producer of misleading corporate narratives.

This tension motivates the present review. Existing reviews have already examined the broader relationship between AI and sustainability reporting. Mustafa et al. (2025) reviewed 135 peer-reviewed articles covering AI technologies and sustainability reporting, while Vilchez Olivares and Astorga De La Cruz (2026) synthesised 45 peer-reviewed articles on AI and data analytics in sustainable financial reporting and ESG disclosure. Other reviews have examined AI, greenwashing, and sustainability reporting (Moodaley & Telukdarie, 2023) and LLM applications in sustainability reporting (Mousavian Anaraki, Croce, & Basili, 2025). These studies provide an important foundation, but the rapid development of generative AI creates a narrower question that deserves dedicated synthesis: how does GenAI affect the quality of sustainability disclosures, through which mechanisms can it facilitate greenwashing, and what forms of human oversight are required to preserve reporting reliability?

Accordingly, this review focuses specifically on the intersection of GenAI and sustainability reporting quality rather than treating AI as a single homogeneous technology. The review distinguishes between AI used to analyse or score existing disclosures and GenAI used to create or transform disclosure content. This distinction is important because analytical AI can improve detection and measurement, whereas generative systems can directly alter the information presented to stakeholders. The paper also treats human oversight as an analytical dimension rather than a purely managerial recommendation. Human review determines whether generated content is supported by evidence, whether material information has been omitted, whether claims are consistent with underlying performance, and whether the final disclosure complies with applicable reporting requirements.

1.1 Research Problem and Gap

The central problem is that sustainability reporting quality has two potentially competing dimensions in an AI-enabled reporting environment. On one side, AI can increase processing capacity and improve the identification of relevant information. On the other side, GenAI can increase the speed and sophistication of narrative production without necessarily improving the underlying evidence. A system may therefore make a report clearer and more persuasive while leaving its substantive reliability unchanged. This distinction is especially important for greenwashing, where the risk concerns the

relationship between corporate claims and underlying sustainability performance rather than the grammatical quality of the disclosure.

The literature gap is consequently not simply that GenAI research is recent. A more defensible gap is that existing scholarship has often examined AI-enabled sustainability reporting, ESG disclosure measurement, greenwashing detection, and GenAI-generated text in separate streams. The emerging evidence now permits these streams to be synthesised around a common question: under what conditions does GenAI support disclosure quality, and under what conditions does it increase the risk that high-quality language masks low-quality evidence? Recent empirical studies provide important pieces of this relationship, but the field still lacks an integrated synthesis that connects disclosure-quality dimensions, greenwashing mechanisms, and human oversight.

1.2 Research Questions

RQ1. How is generative AI being used in sustainability reporting, and what dimensions of disclosure quality are affected?

RQ2. What mechanisms connect generative AI with greenwashing and reduced credibility in sustainability reporting?

RQ3. What forms of human oversight and governance are identified as necessary to maintain reliable and accountable AI-assisted sustainability reporting?

RQ4. What methodological and theoretical gaps remain, and what research agenda follows from the emerging evidence?

1.3 Contribution of the Review

This review makes four contributions. First, it narrows the broad AI-sustainability reporting literature to the specific capabilities and risks of generative AI. Second, it synthesises disclosure quality as a multidimensional construct rather than equating quality with disclosure volume or readability. Third, it integrates greenwashing into the quality discussion by examining how generative systems may influence both the substance and presentation of sustainability claims. Fourth, it develops a human-in-the-loop governance model that connects AI-assisted reporting activities with verification, accountability, and assurance. The contribution is therefore conceptual and integrative rather than causal: the review does not claim that GenAI universally improves or worsens sustainability reporting.

2. MATERIALS AND METHODS

The study is designed as a systematic literature review with thematic synthesis. Systematic reviews are appropriate where a research field is fragmented and rapidly developing because they provide a transparent approach to identifying, assessing, and synthesising prior research (Snyder, 2019). The reporting structure follows the principles of PRISMA 2020, which emphasises transparent reporting of the rationale, search process, eligibility criteria, selection process, synthesis methods, and limitations of a systematic review (Page et al., 2021). The review also follows the research-integrity requirement that a systematic review should not claim a reproducible database protocol unless the databases, search terms, screening decisions, and evidence base can actually be documented.

2.1 Search Strategy

The search was conducted in September 2026 using structured scholarly web searches directed toward publisher pages, institutional repositories, and indexed academic records. The search strategy was designed around four concept groups: (1) generative AI and LLMs, (2) sustainability reporting and ESG disclosure, (3) disclosure quality and greenwashing, and (4) human oversight, assurance, and governance. Search combinations included terms such as “generative AI” AND “sustainability reporting”; “generative AI” AND “ESG disclosure”; “large language models” AND “sustainability reporting”; “AI” AND “ESG disclosure quality”; “generative AI” AND greenwashing; and “AI” AND “sustainability assurance.”

The search deliberately included recent studies from 2023 onward because the emergence of widely accessible generative conversational AI created a materially different reporting environment from earlier machine-learning applications. Earlier sources were retained when they were necessary to explain systematic-review methodology, sustainability-reporting standards, or the conceptual foundations of AI-enabled reporting. Peer-reviewed journal articles were prioritised. Official standard-setting materials from the IFRS Foundation and GRI were included for authoritative descriptions of reporting

requirements and reporting principles. Preprints and non-peer-reviewed sources were not treated as primary evidence for substantive findings when a peer-reviewed version was available.

2.2 Inclusion and Exclusion Criteria

Studies were included when they met all of the following criteria: (a) the study addressed corporate sustainability reporting, ESG disclosure, sustainability assurance, greenwashing, or a directly related reporting activity; (b) AI, machine learning, NLP, LLMs, or generative AI was a substantive component of the study; (c) the source provided empirical evidence, a systematic review, a conceptual framework, or a clearly articulated research agenda relevant to the research questions; and (d) sufficient bibliographic information was available to verify the source. Studies focused exclusively on AI applications unrelated to corporate reporting were excluded. General ESG studies that did not address AI or computational analysis were also excluded from the core synthesis.

2.3 Screening and Evidence Synthesis

The screening process proceeded in three stages. First, titles and abstracts or publisher summaries were examined for topical relevance. Second, the full accessible article record was checked where necessary to confirm the study's purpose, method, findings, and relevance. Third, included studies were grouped into analytical themes rather than summarised one by one. This thematic approach follows the Master Profile supplied for this project, which requires synthesis across sources, explicit identification of convergence and disagreement, and separation of documented evidence from interpretation. The evidence was coded into five fields: AI function, reporting-quality dimension, risk or benefit mechanism, role of human oversight, and implications for future research.

Because direct subscription-level access to Scopus and Web of Science was not available in the present drafting environment, the review does not report a fabricated database hit count or a false PRISMA flow number. This is an important methodological limitation. The final manuscript can be upgraded to a fully reproducible database-based systematic review by rerunning the stated search strings in Scopus and Web of Science and documenting identification, duplicate removal, screening, eligibility, and inclusion counts. The substantive synthesis presented here is therefore based on verified peer-reviewed and authoritative sources that were accessible during the review process, rather than on an invented database count.

2.4 Analytical Framework

The synthesis uses a three-layer framework. The first layer is the AI function: generation, summarisation, extraction, classification, scoring, detection, or assurance support. The second layer is reporting quality: readability, comparability, informativeness, credibility, quantitative evidence, target accountability, and reporting infrastructure. The third layer is governance: human verification, evidence reconciliation, materiality judgment, approval, auditability, and assurance. Greenwashing is treated as a cross-cutting risk because it can emerge when generated language becomes more positive or persuasive without a corresponding improvement in the underlying evidence.

AI function	Potential reporting benefit	Principal risk	Required control
Text generation	Faster drafting and standardised language	Unsupported claims, narrative inflation, greenwashing	Human factual verification and evidence reconciliation
Summarisation	Improved accessibility and reduced information overload	Omission of material information	Completeness checks against source records
Information extraction	Scalable identification of ESG indicators	Extraction error and context loss	Benchmarking against human-coded samples
ESG scoring	Consistent large-scale measurement	Model-dependent scores and hidden assumptions	Transparent codebook and validation
Greenwashing detection	Identification of suspicious claims	False positives or false negatives	Human review and multi-source validation
Assurance support	Faster review of large document sets	Automation bias and over-reliance	Accountable professional judgment

3. FINDINGS

3.1 The Literature Is Moving from General AI Toward Generative AI

The first finding is that the literature is evolving rapidly. Earlier research focused heavily on conventional AI, machine learning, NLP, and automated analysis of sustainability information. Moodaley and Telukdarie (2023) identified the intersection of greenwashing, sustainability reporting, and AI as underexplored. Their review showed that AI was already being considered as a tool for analysing large volumes of sustainability information and detecting potentially misleading disclosures. De Villiers et al. (2024) then explicitly considered the implications of generative AI for sustainability accounting and reporting, identifying both opportunities and risks. The more recent reviews by Mustafa et al. (2025), Mousavian Anaraki et al. (2025), and Vilchez Olivares and Astorga De La Cruz (2026) demonstrate that the broader AI-reporting field has expanded substantially.

The newer literature differs from earlier AI studies because LLMs can perform multiple language-based functions within the same reporting workflow. Mousavian Anaraki et al. (2025) reviewed LLM and NLP approaches to sustainability reporting and highlighted applications in information extraction, classification, and greenwashing detection. Zou et al. (2025) developed ESGReveal, an LLM-based approach for extracting structured information from ESG reports. These studies demonstrate that LLMs can reduce the cost of processing unstructured disclosure text and can support more systematic comparison across firms.

However, the emergence of generative AI changes the unit of analysis. When AI is used to extract information, the main concern is whether the model correctly represents information that already exists. When AI generates disclosure text, the concern becomes broader: whether the generated narrative accurately represents the company's evidence, whether material information is omitted, and whether the style of the generated text creates an impression that exceeds the underlying performance. The literature therefore needs to distinguish AI-assisted analysis from AI-assisted authorship.

3.2 Sustainability Reporting Quality Is Multidimensional

The second finding is that sustainability reporting quality cannot be measured adequately by disclosure volume. Liu, Yuan, and Zhu (2026) identify readability, comparability, informativeness, and credibility as important dimensions of ESG disclosure quality. Recent empirical work further demonstrates the value of more specific indicators. Jung, Che, and Lee (2026), for example, examine quantitative evidence, target accountability, and reporting infrastructure through a composite Disclosure Quality Index. Park (2026) compares human coding, rule-based automation, and LLM semantic scoring and finds that the scoring architecture itself can influence measured disclosure quality.

These findings are important for evaluating GenAI. A generated report may be highly readable but poorly informative if it uses broad claims without measurable evidence. It may be comparable in structure while still failing to provide credible performance information. Similarly, a report may contain a large amount of text without improving accountability. Quality should therefore be conceptualised as a combination of linguistic, informational, evidentiary, and governance characteristics.

Quality dimension	**Meaning in sustainability reporting**	**GenAI opportunity**	**GenAI risk**
Readability	Clarity and accessibility of disclosure	Clearer language and summaries	Polished language may conceal weak evidence
Comparability	Consistency across firms and periods	Standardised structure and terminology	Template-driven similarity may reduce substantive specificity
Informativeness	Decision-useful information about performance, risks and opportunities	Faster extraction and summarisation	Material information may be omitted during summarisation
Credibility	Supportability and trustworthiness of claims	Evidence-linked drafting and consistency checks	Hallucinated or unsupported statements

Quantitative evidence	Specific metrics, amounts and measurable outcomes	Automated identification of numerical evidence	Numbers may be reproduced without adequate context
Target accountability	Clear targets, timelines and responsibility	Automated target extraction	Ambiguous targets may be converted into persuasive narratives
Reporting infrastructure	Frameworks, assurance, controls and governance supporting disclosure	Automated compliance checks	False confidence in compliance based on text similarity

3.3 GenAI Can Improve the Efficiency of Sustainability Reporting

The literature supports several potential benefits of GenAI and related LLM technologies. First, these systems can process large volumes of unstructured text more quickly than conventional manual approaches. This is relevant because sustainability reports contain extensive narrative information that must be compared across firms and periods. LLM-based extraction can convert unstructured statements into structured ESG indicators, enabling researchers and reporting teams to analyse information at scale (Zou et al., 2025).

Second, GenAI can improve accessibility. LLMs can summarise lengthy sustainability reports and translate technical reporting language into more accessible forms. Research on LLM-based reading of sustainability reports indicates that machine-assisted analysis can provide useful signals but may diverge from human reading when important visual or contextual information is present (Jhan & Hsieh, 2026; see also the related evidence reported in recent LLM-based ESG research). This suggests that AI can be valuable as an analytical complement rather than a replacement for human interpretation.

Third, AI can support measurement consistency. Park (2026) shows that LLM-based semantic scoring can produce stronger convergence with human-coded disclosure-quality benchmarks than a simple rule-based approach in the studied Korean sample. This does not establish that LLMs are inherently more accurate in all contexts, but it demonstrates that semantic models can capture dimensions of disclosure that are difficult to identify using simple dictionaries. Such tools may therefore strengthen the scalability of accounting research and sustainability assurance.

Fourth, AI can support assurance and control activities. Professional guidance and emerging practice indicate that AI can be used to review large sets of environmental statements and identify inconsistencies or areas requiring further investigation. The value of such systems is greatest when they function as review and exception-detection tools rather than autonomous substitutes for professional judgment. This distinction is consistent with the broader evidence that AI can improve the processing of ESG information while still requiring governance and validation.

3.4 GenAI Can Also Increase Greenwashing Risk

The most important negative finding concerns greenwashing. Greenwashing occurs when sustainability communication creates a misleadingly positive impression about an organisation's environmental or broader sustainability performance. AI does not need to invent a completely false statement to facilitate greenwashing. It can also contribute through selective emphasis, omission, vague language, positive framing, or the transformation of weak evidence into persuasive narrative. This makes the relationship between GenAI and greenwashing fundamentally a reporting-quality issue.

Dimes et al. (2026) provide the clearest recent empirical evidence. In their experiment, participants used ChatGPT to produce sustainability reports, and the resulting reports contained significantly higher levels of greenwashing than real reports. Participants made few changes to the generated content, suggesting that users may accept AI-produced text without sufficiently checking it against genuine corporate evidence. Importantly, participants also perceived the AI-generated reports as more optimistic, confident, and trustworthy. The study therefore identifies a dangerous combination: higher persuasive quality may coexist with lower substantive quality.

This finding is consistent with the conceptual concerns identified by de Villiers et al. (2024), who argued that generative AI may facilitate greenwashing in sustainability reporting. It also extends earlier research on AI and greenwashing by showing that the problem is not only whether AI can detect misleading claims. The technology can also participate in producing the claims that later need to be detected. This

creates a dual-use problem. The same technological capabilities that improve analysis can also increase the sophistication of impression management.

The risk can be understood through four mechanisms. First is narrative amplification, where AI makes a modest sustainability initiative sound more extensive or strategic. Second is selective disclosure, where the system emphasises positive information while giving less prominence to negative or uncertain evidence. Third is evidentiary decoupling, where claims become separated from the underlying data or source records. Fourth is credibility transfer, where polished language creates an impression of reliability that is not justified by the quality of the evidence. These mechanisms explain why readability and credibility should not be treated as interchangeable.

3.5 Human Oversight Is a Core Quality Mechanism

The third major finding is that human oversight is repeatedly positioned as necessary, although the literature is still developing precise models for implementing it. The problem is not simply that humans may make mistakes. It is that GenAI systems can produce outputs that appear plausible and complete, which may encourage automation bias. When users assume that a fluent output is correct, they may perform less substantive verification. Dimes et al. (2026) provide empirical support for this concern because participants made relatively few changes to AI-generated sustainability reports.

Human oversight should therefore be understood as a set of distinct control activities. The first is source verification: every material claim should be traceable to underlying records. The second is materiality judgment: humans should determine whether relevant positive and negative impacts have been appropriately represented. The third is reconciliation: generated narratives should be checked against quantitative indicators, operational records, financial information, and prior disclosures. The fourth is compliance review: the final report should be assessed against the applicable reporting framework. The fifth is accountability: a named responsible person or function should approve the final disclosure.

Human oversight is especially important because reporting standards involve judgments that cannot always be reduced to textual pattern recognition. GRI standards require organisations to identify material topics based on the significance of their impacts on the economy, environment, and people. IFRS S1 similarly focuses on sustainability-related risks and opportunities that could reasonably be expected to affect an entity's prospects. These judgments depend on organisational context, evidence, and professional assessment. GenAI may support the process, but it should not silently determine materiality or accountability.

3.6 The Emerging Evidence Supports a Human-in-the-Loop Model

The synthesis suggests that the relationship between GenAI and reporting quality is conditional rather than linear. GenAI is most likely to improve quality when it is used for bounded, evidence-linked tasks and when outputs remain subject to substantive human review. It is more likely to undermine quality when it is used to generate unrestricted narrative from incomplete inputs and when reviewers evaluate style rather than evidence.

Reporting stage	Appropriate GenAI role	Human responsibility	Quality safeguard
Data collection	Locate and organise relevant documents	Confirm source completeness	Source register
Data extraction	Extract ESG indicators and claims	Validate sampled outputs	Human benchmark testing
Drafting	Generate preliminary narrative	Verify every material claim	Evidence-to-text reconciliation
Materiality assessment	Surface potentially relevant issues	Make final materiality judgment	Documented judgment process
Greenwashing review	Flag potentially misleading claims	Investigate context and performance	Multi-source comparison
Compliance review	Map disclosures to reporting requirements	Approve compliance conclusion	Standard-specific checklist
Final reporting	Improve structure and readability	Take accountability for final report	Named approval and audit trail

3.7 Evidence Map of the Reviewed Literature

Study	Study type	Main focus	Key implication
Moodaley & Telukdarie (2023)	Systematic review	AI, greenwashing and sustainability reporting	Intersection was historically underexplored; AI has detection potential
de Villiers et al. (2024)	Conceptual analysis	GenAI text generation and processing	GenAI affects reporting, assurance and use; greenwashing risk requires research
Mustafa et al. (2025)	Systematic review	AI and sustainability reporting	Field is fragmented; stronger frameworks and governance are needed
Mousavian Anaraki et al. (2025)	Systematic review	LLMs and sustainability reporting	LLMs support extraction, classification and greenwashing analysis
Zou et al. (2025)	Empirical/methodological	LLM-based ESG extraction	LLMs can structure unstructured ESG information at scale
Liu et al. (2026)	Review	AI and ESG disclosure quality	Quality includes readability, comparability, informativeness and credibility
Dimes et al. (2026)	Experiment	GenAI and greenwashing	AI-generated reports showed higher greenwashing and higher perceived credibility
Park (2026)	Empirical/methodological	Human, rule-based and LLM scoring	Scoring architecture affects measured disclosure quality
Jung et al. (2026)	Empirical	LLM-assisted disclosure quality	Composite quality measures can relate to external ESG evaluations
Vilchez Olivares & Astorga De La Cruz (2026)	Systematic review	AI/data analytics in reporting	Four broad streams: NLP, ML, assurance/governance, and regulation

4. DISCUSSION

4.1 Answer to RQ1: How Does GenAI Affect Disclosure Quality?

The evidence suggests that GenAI affects different dimensions of reporting quality in different ways. It has the strongest positive potential for scalability, readability, information extraction, classification, and standardised presentation. These capabilities can reduce the time required to process large disclosure datasets and can make sustainability information more accessible. The literature on LLM-based extraction and scoring provides evidence that semantic models can identify and structure information that would otherwise require extensive manual work (Mousavian Anaraki et al., 2025; Park, 2026; Zou et al., 2025).

However, the effect on credibility and informativeness is conditional. A report can be more readable without being more truthful. It can also contain more standardised language without being more comparable in substantive terms. Therefore, GenAI should be understood as an enabling technology rather than a quality guarantee. Quality improvements require the combination of accurate source data, appropriate prompts or codebooks, validation procedures, and human accountability.

4.2 Answer to RQ2: How Does GenAI Facilitate Greenwashing?

GenAI can facilitate greenwashing because it reduces the cost of producing coherent and positive sustainability narratives. Traditional greenwashing may require communication expertise and

significant time to construct. Generative systems can produce polished language quickly and can adapt the same underlying information into multiple persuasive formulations. This does not mean that all AI-generated sustainability communication is greenwashing. Rather, the technology increases the capability to communicate selectively or persuasively, making controls more important.

The evidence from Dimes et al. (2026) is particularly important because it shows that the risk is observable in an experimental setting. The AI-generated reports were not merely grammatically different. They exhibited more greenwashing while being perceived as more credible. This finding challenges a common assumption that better language improves reporting quality. In fact, when language quality improves faster than evidentiary quality, the gap between perceived credibility and substantive credibility may increase.

4.3 Answer to RQ3: What Human Oversight Is Needed?

Human oversight should operate at several points rather than only at final publication. Early-stage oversight is needed to determine the source data and reporting boundaries. Mid-stage oversight is needed to review generated claims and materiality judgments. Final-stage oversight is needed to approve the report and document accountability. Assurance providers can add an independent layer, particularly where sustainability information is subject to external assurance requirements.

The appropriate principle is therefore not "human approval of AI output" in a superficial sense. It is "human verification of evidence and judgment." A reviewer who only checks grammar cannot detect many forms of greenwashing. A reviewer must compare generated claims with quantitative indicators, source documents, targets, prior-year disclosures, and applicable standards. This approach transforms human oversight from a symbolic control into a substantive reporting-quality mechanism.

4.4 Theoretical Interpretation

The findings can be interpreted through an information-processing perspective. Sustainability reporting involves collecting heterogeneous information, transforming it into organisational knowledge, and communicating it to external stakeholders. AI increases processing capacity, but processing capacity does not automatically produce better information. If the input data are incomplete or biased, a more powerful language model can produce a more coherent representation of incomplete information. This explains why AI capability and reporting quality should be analytically separated.

Stakeholder theory provides a complementary interpretation. Sustainability reporting is intended to address information needs extending beyond management to investors, regulators, employees, communities, civil society, and other affected groups. If GenAI makes reports more persuasive without improving their evidentiary basis, information asymmetry may not decline and may even become harder to detect. Human oversight and assurance can therefore be viewed as mechanisms that protect stakeholders from the information risks created by scalable automated communication.

4.5 Practical Implications

For accounting professionals, the evidence suggests that GenAI should be deployed through controlled workflows. Organisations should define which reporting tasks may be automated, require evidence links for material claims, maintain records of AI-generated and human-edited content where appropriate, and establish escalation procedures for uncertain outputs. Accountants and sustainability professionals should receive training not only in operating AI tools but also in identifying hallucination, unsupported claims, selective disclosure, and automation bias.

For assurance providers, GenAI creates both an opportunity and a new assurance risk. AI can help assurance teams examine larger quantities of narrative and identify inconsistencies. However, the same technology may be used by preparers to produce sophisticated narratives. Assurance therefore needs to consider the provenance of information, the controls governing AI use, and the relationship between narrative claims and underlying performance data.

For regulators and standard setters, the findings support greater attention to AI governance within sustainability reporting. Future reporting guidance may need to clarify expectations concerning human accountability, traceability of AI-assisted disclosures, documentation of material judgments, and controls over generated content. The objective should not be to prohibit AI-assisted reporting. Instead, regulatory frameworks should ensure that technological efficiency does not weaken the accountability and verifiability of sustainability information.

4.6 Implications for Accounting Research

The accounting literature should move beyond broad questions about whether AI is beneficial. Future studies should examine specific reporting tasks and measurable quality outcomes. For example, researchers can compare AI-assisted and human-only reporting processes using the same underlying evidence and assess differences in quantitative support, target specificity, materiality coverage, and greenwashing. Research should also distinguish between AI used by the reporting preparer and AI used by the assurance provider, because these uses create different incentives and control problems.

The literature should also address cross-language and cross-country settings. Current evidence is concentrated in particular markets and often in English-language reporting. Yet sustainability reporting is increasingly international, and LLM performance can vary by language, cultural context, regulatory environment, and reporting standard. Research in emerging markets is particularly valuable because reporting capacity, assurance infrastructure, digital maturity, and institutional enforcement may differ substantially from advanced economies.

5. CONCLUSION AND RECOMMENDATIONS

This systematic literature review examined how generative AI is reshaping sustainability reporting quality through three connected dimensions: disclosure quality, greenwashing, and human oversight. The evidence indicates that GenAI and related LLM technologies can improve the efficiency and scalability of sustainability information processing. They can support extraction, classification, summarisation, scoring, and the preparation of clearer disclosures. Recent research also shows that LLMs can contribute to more systematic measurement of ESG disclosure quality and can help researchers process large volumes of corporate reporting information.

At the same time, the evidence does not support the conclusion that GenAI automatically improves sustainability reporting quality. The most important risk is that linguistic quality can improve faster than evidentiary quality. GenAI can produce fluent, positive, and credible-sounding sustainability narratives, and recent experimental evidence indicates that such narratives can contain more greenwashing. This creates a distinctive accounting risk because stakeholders may evaluate the quality of communication rather than the quality of the underlying evidence.

The review therefore concludes that the effect of GenAI on sustainability reporting is conditional. GenAI is most beneficial when it operates within an evidence-based reporting architecture that includes reliable source data, explicit reporting criteria, transparent AI use, human verification, documented materiality judgments, and accountable final approval. Human oversight is not merely an ethical safeguard; it is part of the reporting-quality mechanism. The appropriate model is a human-in-the-loop system in which AI increases processing capacity while humans retain responsibility for evidence, judgment, accountability, and final disclosure.

5.1 Recommendations

First, organisations should establish formal GenAI governance policies for sustainability reporting. These policies should define approved use cases, prohibited uses, verification requirements, data-handling rules, and responsibility for final approval.

Second, AI-assisted sustainability disclosures should be linked to evidence. Material claims should be traceable to underlying operational, financial, environmental, social, or governance records. Where a generated statement cannot be supported, it should not be included as an established fact.

Third, reporting teams should evaluate quality across multiple dimensions. Readability should be assessed together with quantitative evidence, comparability, informativeness, credibility, target accountability, and reporting infrastructure. A readable report should not automatically be classified as a high-quality report.

Fourth, organisations and assurance providers should introduce explicit greenwashing controls for AI-generated text. These controls should examine selective disclosure, excessive positive framing, vague claims, missing negative information, unsupported causal statements, and discrepancies between narrative claims and performance indicators.

Fifth, regulators and standard setters should encourage traceability and accountability for AI-assisted reporting. Future guidance should clarify how organisations should document material AI use, preserve evidence trails, and assign responsibility for generated content.

Sixth, researchers should conduct controlled empirical studies comparing human-only, AI-assisted, and AI-generated sustainability reporting. Such studies should measure both perceived credibility and substantive reporting quality because the two may diverge.
Seventh, future research should examine the interaction between GenAI and sustainability assurance. The most important unresolved question is not whether AI can read a sustainability report, but whether an AI-enabled reporting and assurance ecosystem can improve the correspondence between what companies claim and what they actually do.

5.2 Limitations and Future Research

This review has several limitations. First, the literature is developing rapidly, so new studies may change the balance of evidence quickly. Second, the present review was conducted using accessible scholarly publisher and academic-index records rather than direct subscription access to Scopus and Web of Science. Consequently, no database hit count or PRISMA flow number is reported here. Third, the evidence base includes different study designs, including conceptual papers, systematic reviews, experiments, and empirical text-analysis studies, which limits direct comparison. Fourth, the field remains geographically and linguistically uneven. These limitations mean that the review should be interpreted as a structured synthesis of verified evidence rather than as a definitive census of every publication in the field.
A future full-scale review should register a reproducible protocol, search Scopus and Web of Science using the complete search strings, remove duplicates programmatically, apply independent screening by at least two reviewers, record reasons for exclusion, assess study quality, and publish the final evidence table and PRISMA flow counts. A subsequent meta-analysis may become possible if enough comparable empirical studies report common measures of disclosure quality or greenwashing.

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AUTHOR'S NOTE ON REVIEW SCOPE

This manuscript was prepared as a structured systematic literature review draft using verified scholarly and authoritative sources available during the research process. In accordance with the supplied Universal Academic Writing Master Profile, no database counts, coding procedures, reviewer actions, or study-selection statistics have been invented. Before journal submission, the author should rerun the search in the databases required by the target journal, complete the screening record, and reconcile the final reference list and PRISMA flow diagram with the actual search history.

DIGITAL TECHNOLOGY ADOPTION BY REAL ESTATE FIRMS FOR ENHACEMENT OF EMPLOYEE PRODUCTIVITY IN REAL ESTATE ACTIVITIES IN KADUNA, NIGERIA

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ABSTRACT
Digital technology adoption has become a critical driver of organizational performance across industries, yet its specific influence on employee productivity within real estate firms in emerging economies remains underexplored. This study investigated digital technology adoption by real estate firms for enhancement of employee productivity in real estate activities in Kaduna State, Nigeria. The study aimed to: (i) identify the most common digital technologies adopted by real estate firms; (ii) determine the factors affecting digital technology adoption; (iii) assess the level of employee productivity with digital technology adoption; and (iv) determine the effects of digital technology factors on employee productivity. A quantitative research approach with a cross-sectional survey design was employed. The study targeted registered Estate surveyors and valuers in Kaduna State, with a sample frame of 333 registered Estate surveyors and valuers. Using random sampling, 147 valid responses were obtained and analyzed. Data were collected using a structured 5-point Likert scale questionnaire. Descriptive statistics (mean ranking) and inferential statistics (multiple regression analysis) were employed for data analyss. Artificial Intelligence (AI) was the only technology with "High Awareness" (M=3.73), while specialized tools like BIM (M=2.90) and 3D Laser Scanning (M=2.93) showed lowest recognition. Performance Expectancy (M=3.82) and Effort Expectacy (M=3.66) were the strongest adoption drivers. Employee productivity was moderate (M=3.10), with problem-solving capabilities ranking highest (M=3.29). The regression model explained 55% of productivity variance (R^2=0.550, F=37.893, $p<0.001$), with Social Influence (β=0.395) and Effort Expectancy (β=0.315) as the most significant predictors. Digital technology adoption significantly enhances employee productivity in real estate firms, with social and ease-of-use factors outweighing purely technical considerations. Real estate firms should implement targeted training for specialized digital tools (BIM, LiDAR), straigthen direct supervisor-peer digital advocacy, transition from baseline to high-precision applications, and prioritise intuitive user interfaces alongside collaborative digital cultures to maximize productivity returns. Finally there is need for further study to determine how digital adoption moderate the relationship between remote work model and clients service effectiveness in professional services firms..
Keywords: Information Management Systems, Residential Property Management System, Technology Adoption, Technology Acceptance Model, Awareness, Perceived Usefulness, Ease of Use

1. INTRODUCTION
Digital technology adoption is now a key driver of operational efficiency, innovation, decision-making, cost reduction, customer service, and competitive advantage for firms in dynamic markets (Oduro, De Nisco, & Mainolfi, 2023; Verhoef *et al.,* 2021). In real estate, ICT tools such as cloud computing, AI, big data, IoT, GIS, Soft Data Server, PropTech, virtual reality tours, and property management software have transformed marketing, appraisals, valuation, and property management (Droj, Kwartnik-Pruc & Droj, 2024; Starr, Saginor & Worzala, 2021). These technologies improve client experience, speed up processes, and provide data-driven insights for strategic planning.
However, benefits depend heavily on staff proficiency. ICT tools like application software, drones, wireless sensors, and cloud platforms are now indispensable for estate surveyors and valuers

(Oluwunmi, Role & Umeh, 2022), but insufficient ICT skills among staff remain a major barrier (Aldosari, Eid & Chen, 2022). Employee productivity is also influenced by workspace conditions, communication, safety, and supervisor support (Voordt & Jensen, 2023; Hamed *et al.*, 2023). Training is critical: customized, continuous programs with practical simulations and change management support can boost competence, confidence, and adoption of new technologies (Aldosari, Eid & Chen, 2022; Oluwunmi & Agara, 2023). Without proper training and a supportive work environment, digital tools may not deliver expected gains. Real estate companies must therefore invest in training, technical support, and a culture that welcomes digital transformation to enhance productivity and growth.

Despite the potential of digital technologies, real estate firms face several adoption challenges. Workers often resist new tools due to familiarity with old processes and fear of the unknown (Malik *et al.*, 2023). Poor training, weak integration, technical problems, and complex interfaces lead to mistakes, frustration, and reduced productivity (Parker & Grote, 2022; Khin & Ho, 2019). Data security/privacy concerns and lack of leadership buy-in further hinder adoption (Khin & Ho, 2019).

Training programs are often too technical and lack practical, job-specific applications, leaving employees confused and unable to apply tools in real work situations (Schwarzmüller *et al.*, 2018). Without exercises, simulations, and continuous support like tutorials or help desks, confidence and proficiency remain low (Fleming *et al.*, 2020; Borges *et al.*, 2021). Negative managerial attitudes also worsen the problem; managers who distrust technology fail to communicate its benefits or invest in training, creating resistance and a why bother" mindset among staff (Trenerry *et al.*, 2021; Diamantidis & Chatzoglou, 2019).

While previous studies have examined staff productivity and digital adoption broadly, there is limited research on comprehensive, context-specific strategies for real estate companies in Kaduna State, Nigeria to use digital technologies to improve staff productivity. This study therefore aims to: 1)

- identify the most common digital technologies in real estate firms for enhancement of employee productivity for real estae activities in Kaduna State, Nigeria.
- determine the factors affecting digital technology adoption in real estate services in the study area.
- assess the level of real estate employee productivity with the adoption of digital technology in the study area.
- determine the effects of digital technology factors on real estate employee productivity in the study area.

2. LITERATURE REVIEW

2.1 Digitalization of Real Estate Firms

Digitalization refers to the integration of digital technologies into daily operations to change how work is done, driven by the Fourth Industrial Revolution (4IR) (Ritter & Pedersen, 2020). It differs from digitization, which is simply converting analogue data to digital form. 4IR technologies include cyber-physical systems (CPS), AI, IoT, cloud computing, VR/AR, big data, and mobile apps (Mhlanga & Ndhlovu, 2023). These "smart" technologies enable data transmission without human intervention and allow firms to create virtual representations of physical processes, make decentralized decisions, and automate operations (Acciaro, Renken & El Khadiri, 2020).

2.1.1 Drivers of Digitalization

Adoption is driven by both strategic and operational factors, classified as internal and external (Omrani *et al.*, 2022). Key technological drivers include cloud computing, AI, big data, robotics, AR/VR, and additive manufacturing (Khan *et al.*, 2021; Tantawi *et al.*, 2023). Organizational factors also matter: alignment with organizational identity (Kammerlander *et al.*, 2018), digital attentiveness (Li *et al.*, 2021), digital resources, adaptable structure, and a clear digital growth strategy (Verhoef *et al.*, 2021; Mihu, Pitic & Bayraktar, 2023).

2.1.2 Internal Drivers

Internally, firms adopt digital tech to solve operational problems: reduce costs, improve efficiency in production, shipping, and sourcing, and replace outdated manual processes (Jinru *et al.*, 2021; Omrani *et al.*, 2022). The adoption process is often bottom-up: identify problems, set targets, develop solutions, implement, and adjust (Akpan *et al.*, 2022). Strategically, firms like Amazon, Alibaba, and Google

inspire others to use digital tech for innovation, new products, and sustainability goals (Yang, Fu & Zhang, 2021; Usai *et al.*, 2021). Strategic adoption is top-down, requires senior management commitment, resources, and alignment with long-term goals, but may face more uncertainty and internal resistance due to workflow changes (Wrede, Velamuri & Dauth, 2020; Li, Dai & Cui, 2020).

2.1.3 External Drivers

Externally, customer demand for digital products/services pushes firms to adopt tech for better client relations and marketing (Matarazzo *et al.*, 2021; Li, Dai & Cui, 2020). Supply chain pressure is also key: when dominant partners adopt a digital system, others follow to remain competitive (Yang, Fu & Zhang, 2021). Competitive pressure from rivals' tech advances and disruptive new entrants, plus regulatory changes, also force digital transformation (Steiber *et al.*, 2020; Osmundsen, Iden & Bygstad, 2018). Firms fear being left behind if they don't adopt, leading to industry-wide diffusion (Ghobakhloo & Ching, 2019).

2.2 Barriers to Digitalization by Real Estate Firms

Despite benefits, several barriers exist. Technical, individual, organizational, cultural, and environmental hurdles, plus skills gaps, are common (Vogelsang *et al.*, 2019). Poor leadership focused on digitalization slows adoption (Tsou & Chen, 2022). Firms that don't digitize face time-consuming processes, data overload, poor data quality, lost documents, missed information, and lost business opportunities (Rajab, Gazal & Alkattan, 2020).

Paper-based systems reduce productivity: documents are easily damaged, hard to locate, and require physical storage (Vuori, Helander & Okkonen, 2019). Other challenges include lack of funds, lack of expertise, complex IT infrastructure, and cybersecurity/data protection risks (Cichosz, Wallenburg & Knemeyer, 2020; Musamali & Muchelule, 2022). The biggest challenge is often developing a successful digital strategy (Kostka, 2022).

2.3 Employee Effectiveness with Digital Technologies

Employees are critical to achieving organizational goals (Syafrizal, Wibisono & Nurhatisyah, 2024).Digitalization changes communication, sales, and information strategies, giving firms competitive advantage (Lin, Yip, Ho, & Sambasivan, 2020). Work effectiveness means achieving targets in quality, quantity, and time (Pajrin *et al.*, 2022; Sedarmayanti, 2010).

Studies show digital tools like intranet, broadband, digital training, websites, social media, and enterprise systems improve productivity and sales (Seclen-Luna *et al.*, 2022). However, benefits depend on integrating tech into organizational structure, not just investment (Ali, Shen & Sun, 2021). Adoption varies by country, industry, firm size, age, staff expertise, and technology level (Gal *et al.*, 2019). Digitalization restructures all functional areas and changes operational paradigms (Ryketeng & Syachbrani, 2023).

2.4 Employees' Productivity in Real Estate Firms

Productivity is the effective generation of output, profit, or results (Almaamari, 2023). It is closely tied to employee performance and is a top priority for organizations (Leito, Pereira & Gonçalves, 2021). It can be measured by output per time period or compared to average output of similar workers (Bellet, De Neve & Ward, 2024).

Productivity is influenced by employee attitudes toward technology, values, and traits (Almaamari, 2023; Rapciewicz Jr., 2022). Workers inspired by digital tools are more innovative and efficient (Gabriel & Aguinis, 2020). Training improves skills and effectiveness (Almaamari & Alaswad, 2021). In real estate, productivity also depends on management: good managers lead, supervise, train, motivate, and create cultures that eliminate inefficient processes and encourage innovation (Paul & Chowdhury, 2020). Higher productivity reduces costs, improves quality, strengthens competitive advantage, and supports economic growth and better wages (Jain, 2020). Aligning productivity with strategic vision motivates innovation and goal achievement (Obama & Kumolu-Johnson, 2019; Anekwe, Osarenoma & Ifeanyichukwu, 2024). In Kenya, cloud computing and tech innovations improved efficiency, cost reduction, and value addition, but infrastructure complexity and poor IT practices remain barriers (Kamau, 2019; Musamali & Muchelule, 2022).

2.5 Digital Technologies Awareness in Real Estate Industry

Digital shift is happening globally, but awareness is uneven (Saull *et al.*, 2020). While most practitioners know AI and Big Data, there's an "awareness gap" for technical tools like BIM and 3D Laser Scanning (Dixon, 2021). Awareness involves not just knowing a tech exists, but understanding its utility, cost, and compatibility with workflows (Apanaviciene *et al.*, 2020).

In emerging markets, lack of awareness campaigns and training is a major barrier to digital maturity (Nwuba *et al.*, 2021). Firms with higher internal awareness are more likely to invest in disruptive tech like Blockchain for land titling and VR for property viewing, gaining competitive advantage (Wouters *et al.*, 2020). Overall, awareness is a critical precursor to adoption and integration of PropTech (Starr *et al.*, 2021).

Conceptual Framework

This research conceptualised employee productivity to be influenced by the technology's performance expectancy, effort expectancy, social influence, and facilitating conditions. This was based on a review of the literature and the pertinent theoretical underpinnings. Professionals providing real estate services may also benefit from the technology's adoption. The conceptual framework, from which the research hypotheses emanated, is presented in figure 2. The operationalisation of the research variables is presented in Chapter 3.

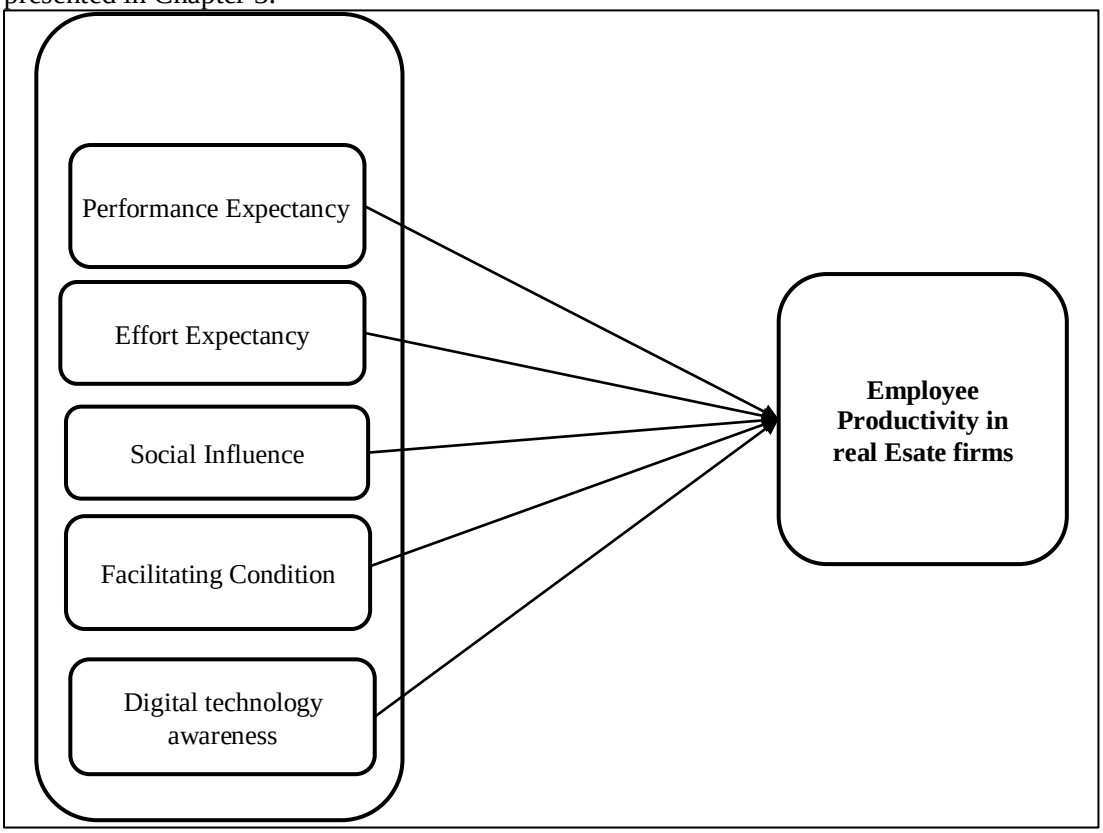


Figure: 1: Conceptual Framework of the Study

3. RESEARCH METHODOLOGY

The element of any good research work depends largely on its methodology which usually encompasses the design, philosophy, sampling strategy and so on. This chapter will delve highly into the design of the methodology adopted for the work. It will touch on core aspects which relate to the objective of the work such as the sampling method, the sample size, the instrument of data collection and others.

3.1Research Design

The research designs adopted for this study are exploratory and descriptive. Therefore, when there is little to no understanding of a subject, exploratory research is a methodological strategy used.

3.2 Research Approach
A quantitative research approach will be adopted in this research due to the nature of the research problem which involves the Strategies for Digital Technology Adoption by Real Estate Firms to enhance employee productivity in Kaduna, Nigeria.

3.3 Research Strategy
There are different research strategy which may include survey, case study, experimental, action e.t.c. The research strategy in this work is cross sectional survey research using sample survey.

3.4 Population of the Study
For this work, only practising estate surveyors and valuers in Kaduna state are the target population because the study focuses on Digital Technology Adoption by Real Estate Firms to Increase Employee Productivity in real estate activities in Kaduna, Nigeria.

3.5 Sampling and Sample Technique
There are 333 registered estate surveyors and valuers in Kaduna (NIESV Kaduna branch, 2024). The sample frame for this study are all the 333 registered estate surveyors and valuers in Kaduna. For this study, the sample size of 175 registered estate surveyors and valuers in Kaduna (Krejcie & Morgan, 1970). For this study, the simple random sampling technique was adopted, which gave equal chance of participation to each member of the sample frame.

3.6 Method of Data Collection
This included the respondents' responses collected from the close-ended questionnaire using statistical instruments. A 5-point Likert scale was used in this work to collect the data. Each point on the scale was assigned a numerical value, which was used to measure attitudes and conduct the investigation. Hence, the data obtained from the instrument was analyzed with relative care. The questionnaire was close-ended and aligned with the actual work; it contained five (5) sections. Section A covered the demographics of the respondents, section B covered awareness of digital technology, section C collected information on factors affecting digital technology adoption, and section D covered employee productivity.

3.7 Method of Data Analysis
This research was analyzed using descriptive and inferential statistics to achieve maximum results. Objectives 1, 2 and 3 were analyzed using descriptive statistical tools with mean ranking, and objective 4 was analyzed using the inferential statistical method of multiple regression. The results were presented in tables. A summary of the analysis is presented in Table 1

Table 1: Summary of the Research Framework

Research Objectives	Data Collection	Method of Data Analysis
RO 1	Questionnaire	Descriptive (Mean Ranking)
RO 2	Questionnaire	Descriptive (Mean Ranking)
RO 3	Questionnaire	Descriptive (Mean Ranking)
RO 4	Questionnaire	Multiple Regression

4. RESULTS AND DISCUSSION
This chapter present the result of analysis conducted on the collected data. The collected data was coded, cleaned and screened to treat the issues of wrong postings, missing data and extreme outlier. Similarly, the normality test of the data as well as the internal consistency of the research constructs was conducted. After establishing the quality criteria of the data, the data was analysed using both descriptive and inferential statistical tools. The detailed results are presented in the following sections. The survey was conducted to collect information from professionals in construction industry on stakeholder management factors including project success. The information was sought from 175 respondents which constitute the sample size of the study.

4.1 Data Normality

This research checked the normality of the data distribution using skewness and kurtosis. George and Mallery (2010) recommended that skewness and kurtosis values of -2 to +2 are considered a symmetry distribution which are suitable for parametric tests and presume a normal distribution. the normality test conducted on the research variables using skewness and kurtosis criterion as recommended by Pallant (2021) and George and Mallery (2010). The result shows that all the variables are within the recommended range of -2 and +2 (George & Mallery, 2010).

4.2 Collinearity test

Multicollinearity in independent variables is determined by assessing the tolerance level and Variance Inflation Factor (Pallant, 2023; Hair *et al.*, 2010). Hair et al. (2010) recommended a rule of thumb for assessing collinearity issues. Multicollinearity exist when the tolerance level is less than 0.1 or when the VIF is greater than 10. Hence, a tolerance level above 0.1 and VIF of less that 10 signify absence of multicollinearity. This criterion is used to assess the collinearity of the research variables as presented in Table 2.

Table 2: Collinearity assessment

Constructs		**Tolerance**	**VIF**
Aggregated Constructs			
DTA	Digital Technology Awareness	0.365	2.233
PE	Performance Expectancy	0.264	3.776
EE	Effort Expectancy	0.279	4.582
SI	Social Influence	0.475	4.522
FC	Facilitating Condition	0.390	4.416
(EP)	**Employee Productivity** (Dependent variable)	Dependent Variable	

Table 2 shows the tolerance level and VIF of the research variables. The tolerance levels range from 0.264 to 0.475 all above the recommended 0.1 minimum. Similarly, the VIFs range from 2.233 to 4.582 all below the recommended minimun of 10. Therefore, the study variables pass the collinearity test and are suitable for multivariate analysis.

4.3 Demographic Information of the Respondents

Table 3: Demographic Information of the Respondents

SN	**Respondents' Details**	**Response**	**Frequency**	**Percent**
1	**Gender**	Male	114	77.6
		Female	33	22.4
		Total	147	100.0
2	**Age**	less than 30 years	25	17.0
		30 – 50 years	93	63.3
		Above 51 years	29	19.7
		Total	147	100.0
3	**Education**	NDHND	31	21.1
		Bachelors degree	93	63.3
		Masters	23	15.6
		Total	147	100.0
4	**Working Experience**	Less than 5 years	21	14.3
		5 – 10 years	90	61.2
		11 – 15 years	24	16.3
		Above 15 years	12	8.20
		Total	147	100.0

The sample consisted of 147 respondents. Regarding gender, the majority were male (77.6%, n = 114), while females comprised 22.4% (n = 33). In terms of age, the largest proportion of participants were

between 30 and 50 years old (63.3%, n = 93), followed by those above 51 years (19.7%, n = 29), and those under 30 years (17.0%, (n = 25). For educational attainment, most respondents held a bachelor's degree (63.3%, n = 93), while 21.1% (n = 31) possessed a National Diploma or Higher National Diploma, and 15.6% (n = 23) held a master's degree. Regarding working experience, the majority reported having between 5 and 10 years of experience (61.2%, n = 90), followed by those with 11 to 15 years (16.3%, n = 24), less than 5 years (14.3%, n = 21), and above 15 years (8.2%, n = 12).

4.4 Assessment of Digital Technologies Adopted by Real Estate Firms

Digital Technologies Awareness was assessed, and the result is presented in Table 4.

Table 4: Digital Technologies Adoption

Digital Technologies	Mean	SD	Remark
Artificial Intelligence (AI)	3.7279	1.18529	Highly Aware
Internet of Things (IoT)	3.1905	1.24049	Moderate Awareness
Cloud Computing	3.1769	1.29647	Moderate Awareness
Virtual Reality (VR)	3.1361	1.22552	Moderate Awareness
Property Technology (Proptech)	3.1361	1.22552	Moderate Awareness
Property Passports Digital Logbooks	3.1020	1.30717	Moderate Awareness
Geographic Information System (GIS)	3.0680	1.27494	Moderate Awareness
Augmented Reality (AR)	3.0340	1.33147	Moderate Awareness
Blockchain	3.0204	1.27392	Moderate Awareness
Digitalization Platforms	2.9796	1.24124	Moderate Awareness
Drones (UAVs)	2.9252	1.23360	Moderate Awareness
3D Laser Scanning (LiDAR)	2.9252	1.21683	Moderate Awareness
Building Information Modeling (BIM)	2.8980	1.22046	Moderate Awareness
Awareness (Aggregated)	3.1015	0.8566	Moderate Awareness

The assessment of digital technologies adoption reveals a range of familiarity among respondents, with Artificial Intelligence (AI) emerging as the most recognized technology. Participants demonstrated a high level of awareness for AI (M = 3.73, SD = 1.19), which was the only category to surpass the "Moderate Awareness" threshold. This suggests a significant penetration of AI concepts within the respondent group compared to more specialized digital tools.In contrast, the majority of the evaluated technologies fell within the "Moderate Awareness" range. Technologies such as the Internet of Things (IoT) (M = 3.19, SD = 1.24), Cloud Computing (M = 3.18, SD = 1.30), and Virtual Reality (VR) (M = 3.14, SD = 1.23) showed consistent mid-level familiarity. Notably, Property Technology (Proptech) shared identical statistical values with VR (M = 3.14, SD = 1.23), indicating a uniform level of moderate exposure to both immersive and industry-specific digital solutions.Further analysis of specialized applications, including Geographic Information Systems (GIS) (M = 3.07, SD = 1.27) and Blockchain (M = 3.02, SD = 1.27), indicates a slight decline in awareness scores, though they remain within the moderate bracket. The technologies with the lowest relative mean scores were Drones (UAVs) (M = 2.93, SD = 1.23), 3D Laser Scanning (LiDAR) (M = 2.93, SD = 1.22) and Building Information Modeling (BIM) (M = 2.90, SD = 1.22).

4.5 Factors Affecting Digital Technology Adoption in Real Estate Firms

The Digital technology adoption factors in Kaduna real estate firms were evaluated using various constructs as presented in Table 5,

Table 5: Digital Technology Adoption

Factors affecting digital technology adoption in real estate firms	Mean	SD	Remark
Performance Expectancy			
Digitalisation helps me complete more work than otherwise possible	3.9864	1.07261	High
Digital tools improve the quality of my work output	3.9252	1.02762	High

Digital technologies increase my chances of achieving work goals	3.8707	1.00186	High
Digital technologies enable me to accomplish tasks more quickly	3.8707	.98809	High
Digital technologies enable effective knowledge sharing with colleagues	3.7483	1.10938	High
Using digitalisation enhances my effectiveness on the job	3.7143	1.05985	High
Digital tools improve my decision-making capabilities	3.6054	1.16782	High
Effort Expectancy			High
My interaction with digital systems is clear and understandable	3.7483	1.06529	High
I find digital tools flexible to interact with	3.6871	1.07781	High
Using digital applications requires minimal mental effort	3.6531	1.10201	High
I find digital technologies easy to use in daily work	3.6259	1.12391	High
It is easy for me to become skilful at using digital technologies	3.6190	.99542	High
Learning to operate digital tools is easy for me	3.6122	1.12536	High
Social Influence			High
Management supports the adoption of digital technologies	3.7075	1.11779	High
The organisational culture promotes digital technology use	3.6939	1.02444	High
People who influence my behaviour think I should use digital tools	3.5714	1.05337	High
Industry peers in real estate sector are adopting digitalisation	3.4694	1.13056	High
My colleagues think I should use digital technologies at work	3.3878	1.06275	Moderate
My supervisors encourage the use of digitalisation for job tasks	3.1088	1.15349	Moderate
Facilitating Condition			
I have the knowledge required to use digital tools	3.5918	.98450	High
Technical support is available when I face difficulties	3.5782	1.02653	High
Clear policies guide the use of digital technologies in my firm	3.5306	1.07465	High
The digital infrastructure in my organisation is reliable	3.4830	1.02271	High
My organisation provides adequate digital training programs	3.4762	1.13072	High
My organisation invests in upgrading digital technologies regularly	3.4150	1.09071	High
Aggregated Mean			
Performance Expectancy	3.8173	.90224	High
Effort Expectancy	3.6576	.92566	High
Facilitating Condition	3.5131	.90022	High
Social Influence	3.4898	.88948	High
Factors Affecting Digital Technology Adoption (Grand Mean)	**3.6195**	**.76123**	**High**

Performance Expectancy emerged as the most significant driver for technology adoption, yielding the highest aggregated mean among all constructs (M = 3.82, SD = 0.90). Within this category, respondents strongly indicated that digitalization allows them to complete more work than otherwise possible (M = 3.99, SD = 1.07) and improves the quality of their work output (M = 3.93, SD = 1.03). These results suggest that real estate professionals primarily value digital tools for their utilitarian benefits and productivity enhancements.

Parallel to performance gains, Effort Expectancy also recorded a high aggregate score (M = 3.66, SD = 0.93). The data suggests a high level of user-friendliness, specifically regarding the clarity of interaction

with digital systems (M = 3.75, SD = 1.07) and the relative ease with which users become skillful in their operation (M = 3.62, SD = 1.00).

The construct of Facilitating Conditions received a high aggregate rating (M = 3.51, SD = 0.90), indicating that the necessary organizational infrastructure is largely in place. Respondents felt most confident in their own knowledge required to use digital tools (M = 3.59, SD = 0.98) and noted the availability of technical support (M = 3.58, SD = 1.03). However, the regular upgrading of digital technologies by the organization (M = 3.42, SD = 1.09) was the lowest-rated factor within this construct, though it remained within the "High" remark category.

Social Influence recorded the lowest aggregate mean among the four factors (M = 3.49, SD = 0.89), yet still maintained a "High" overall remark. While management support (M = 3.71, SD = 1.12) and organizational culture (M = 3.69, SD = 1.02) were viewed as strong catalysts, peer-to-peer influence and supervisor encouragement were notably lower. Specifically, encouragement from supervisors for job tasks (M = 3.11, SD = 1.15) and pressure from colleagues (M = 3.39, SD = 1.06) were the only items in the entire dataset to receive a "Moderate" rather than "High" remark. The Grand Mean for all factors affecting digital technology adoption was M = 3.62 with a standard deviation of SD = 0.76. This indicates a strong inclination toward the adoption of digital tools within the sampled real estate firms.

4.6 Assessment of Employee Productivity

Employee Productivity was assessed, and the result is presented in Table 6.

Table 6: Employee Productivity

Employee Productivity	Mean	SD	Remark
Problem-solving capabilities	3.2925	1.23428	High
Job Satisfaction	3.2585	1.28259	Moderate
Efficiency in completingwork	3.1769	1.27516	Moderate
Contribution to organisational goals	3.1565	1.20899	Moderate
Access to information	3.1429	1.23311	Moderate
Work accuracy	3.0952	1.31552	Moderate
Meeting deadlines (time management) Consistently	3.0816	1.22480	Moderate
Work performance evaluations	3.0612	1.34584	Moderate
Effectiveness in Serving clients	2.9932	1.27406	Moderate
Work flexiblility	2.9388	1.33049	Moderate
Work quality	2.8707	1.28890	Moderate
Employee Productivity (Aggregated)	3.0971	1.06559	**Moderate**

The analysis of employee productivity reveals a varied landscape of performance indicators, with Problem-solving capabilities standing out as the highest-rated attribute (M = 3.29, SD = 1.23). This was the only metric in the productivity set to receive a "High" remark, suggesting that employees feel particularly empowered or effective in addressing workplace challenges.

Most other productivity dimensions were categorized under "Moderate" remarks. Job Satisfaction (M = 3.26, SD = 1.28) and Efficiency in completing work (M = 3.18, SD = 1.28) followed closely, indicating a stable but not exceptional level of output and morale. Interestingly, the contribution to organizational goals (M = 3.16, SD = 1.21) also aligns with this moderate trend, suggesting that while employees are meeting baseline expectations, there remains significant room for growth in aligning individual output with broader firm objectives.

Lower mean scores were observed in areas related to technical precision and external relations. Specifically, Work quality (M = 2.87, SD = 1.29) and Work flexibility (M = 2.94, SD = 1.33) yielded the lowest scores in the dataset. Furthermore, the Effectiveness in serving clients (M = 2.99, SD = 1.27) fell just below the 3.00 threshold, which may indicate that current digital adoption or organizational structures have yet to fully translate into optimized external service delivery. The Employee Productivity (Aggregated) score resulted in a mean of 3.10 (SD = 1.07). This cumulative figure reflects a Moderate level of productivity.

4.7 Effects of Digital Technology Adoption Factors on Employee Productivity in Real Estate Firms

The third objective of this research seeks to determine the effects of Digital Technology Adoption Factors on Employee Productivity in Real Estate Firms, Multiple Regression Analysis (MRA) was employed. Quality evaluations were conducted at the earlier stage of the analysis to ensure that the data meet the multivariate analysis requirements.

4.7.1 Regression Model

The regression model incorporates all the individual factor of digital technology adoption into the regression model as presented in Table 7.

Table 7: Model Summary and ANOVA

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	F	Sig.
1	0.785[a]	0.550	0.517	.65210	37.893	0.000[b]

Table 7 shows the regression model summary and the ANOVA result. The model produced overall R value of 0.785 and R square value of 0.550 with F-statistics of 37.893 which are significant as indicated by p value of 0.000 far below the recommended maximum of 0.05 (Pallant, 2023). This shows that the model predicts about 55 percent of the variation in employee productivity. In other words, about 55 percent of the changes in employee productivity whether high or low can be explained by changes in the factors affecting digital technology adoption. The model is fitted well and good as it produced a strong R square and F statistics values.

The individual influence of each of the factors affecting digital technology adoption on employee productivity is presented by the standardized regression coefficients in Table 11.

Table 8: Regression Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	**T**	**Sig.**
(Constant)	1.212	0.210		5.768	0.000
Digital Technology Awareness	0.215	0.090	0.196	2.382	0.018
Performance Expectancy	0.175	0.102	0.174	1.721	0.002
Effort Expectancy	0.271	0.181	0.315	3.141	0.010
Facilitating Condition	0.293	0.101	0.299	2.908	0.000
Social Influence	0.359	0.082	0.395	4.383	0.000

The regression model demonstrates that all five independent variables are statistically significant predictors of employee productivity. The constant for the model was significant ($B = 1.212$, $t = 5.768$, $p < 0.001$), establishing the baseline for the dependent variable. Among the predictors, Social Influence emerged as the most substantial positive driver (beta = 0.395, $t = 4.383$, $p < 0.001$). This indicates that the organizational environment, management support, and peer expectations are the strongest catalysts for enhancing professional output. Effort Expectancy also showed a strong significant impact (beta = 0.315, $t = 3.141$, $p = 0.010$), suggesting that the perceived ease of use associated with digital tools significantly reduces barriers to productivity.

Facilitating Conditions exhibited a high level of significance ($B = 0.293$, beta = 0.299, $t = 2.908$, $p < 0.001$), emphasizing that the availability of technical support and reliable infrastructure is essential for effective technology utilization. Awareness followed with a significant positive relationship ($B = 0.215$, beta = 0.196, $t = 2.382$, $p = 0.018$), indicating that broader knowledge of available digital technologies directly correlates with improved employee efficiency. Finally, Performance Expectancy was confirmed as a significant positive predictor ($B = 0.175$, beta = 0.174, $t = 1.721$, $p = 0.002$), proving that employees who believe technology will help them achieve their goals are more likely to exhibit higher productivity.

5. CONCLUSION

Real estate firms in Kaduna show high awareness of general digital trends like AI, but lack knowledge of specialized tools like BIM and 3D Laser Scanning. Technology adoption is mainly driven by perceived usefulness and ease of use, with adequate infrastructure and support. However, weak social influence from supervisors and peers limits full digital integration despite a supportive culture. Current digital use has raised productivity to a moderate level, with strong problem-solving but low work quality and flexibility. Regression shows Social Influence and Effort Expectancy are the strongest predictors, explaining 55% of productivity variance.

To achieve high productivity, firms must build a collaborative digital culture and integrate tools intuitively into daily workflows, not just invest in infrastructure.

6. RECOMMENDATIONS

The recommendations are offered based on the findings of the research.

To move beyond general AI awareness, firms should implement targeted training programs for high-precision tools like BIM and 3D Laser Scanning. This will bridge the "knowledge gap" and ensure the workforce is equipped with the specific technical competencies required for modern real estate operations. Management should move beyond general policy and actively foster a culture of direct supervisor and peer-to-peer digital advocacy. Addressing the "moderate" social influence through mentorship and active recognition will create the necessary interpersonal motivation to accelerate technology uptake. Organizations must transition from baseline digital usage to high-precision applications that directly improve work quality and client service effectiveness. Focusing on these specific productivity weaknesses will ensure that digital adoption translates into superior professional excellence rather than just moderate efficiency.

Since Social Influence and Effort Expectancy are the strongest predictors of productivity, firms should prioritize intuitive, user-friendly interfaces and social support systems. Investing in the ease of use and a collaborative digital environment will yield the highest return on investment for overall employee performance.

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VIBRATIONAL RELIABILITY OF BIO-BASED CYLINDRICAL SHALLOW SHELLS UNDER RESONANCE RISK

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Abstract
Natural fiber-reinforced composites exhibit inherent variability in their mechanical properties, which may significantly affect the dynamic response and reliability of structural components. This study investigates the vibrational reliability of cylindrical shallow shells made of an epoxy matrix reinforced with randomly distributed short Alfa fibers, with particular attention to the risk of resonance. Experimental free-vibration tests were first performed to characterize the dynamic behavior of the manufactured shells. A finite element model was then developed and validated against the experimental natural frequencies and mode shapes. To account for uncertainties, the numerical model was coupled with a Monte Carlo simulation in which the mechanical and geometrical properties of the composite shells were considered as random variables characterized by different coefficients of variation. Sensitivity analysis was performed to identify the parameters governing the variability of the first natural frequency, which is particularly critical with respect to resonance. The results show that the composite Young's modulus is the most influential parameter, followed by shell thickness, radius, and chord. Increasing the uncertainty of the input parameters leads to a significant dispersion of the first natural frequency and consequently increases the possibility of approaching resonance conditions. Finally, a reliability analysis based on the safety margin between the excitation frequency and the first natural frequency was used to characterize safe and critical operating regions. The results demonstrate that controlling the variability of the composite Young's modulus is essential for reducing resonance risk and ensuring the reliable design of Alfa fiber-reinforced cylindrical shallow shells.
Keywords: Vibrational reliability; Resonance; Uncertainty; Monte Carlo simulation; Sensitivity analysis; Alfa fibers; Cylindrical shallow shells.

THE EFFECT OF EARNING PER SHARE AND BOOK VALUE ON STOCK RETURN

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ABSTRACT

This study to analyze the fundamental factors that influence the company's stock returns, Earnings Per Share (EPS), Return On Assets (ROA) and stock returns on four samples of computer service sub-sector companies and other devices listed on the Indonesia Stock Exchange in 2013 - 2017, which produced twenty observations. The analysis technique used in this study is to use multiple linear regression models, which are then used to analyze data and test research hypotheses. The research hypothesis was analyzed using simultaneous test and partial test with a significance level of five percent. The results of this study indicate that simultaneous earnings per share and return on assets have a significant effect on stock returns. Partially return on assets has a negative and significant effect on stock returns, while earnings per share has a positive and insignificant effect on stock returns in computer service and other equipment sub-sector companies listed on the Indonesia Stock Exchange.

Keywords: Earning per share, return on assets, stock return

BIOHYDROGEN: ADVANCING SUSTAINABLE ENERGY THROUGH GREEN FUEL TECHNOLOGY

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Abstract
It has become a global agenda to find a sustainable fuel as greenhouse gas emissions are increasing, which in turn heightens environmental concerns. The whole world is in search of environmentally friendly energy options. Hydrogen, similar to electricity, can be considered a versatile energy carrier that can be produced from various primary energy sources, including coal, biomass, natural gas, energy crops, sunlight, waste, wind, and nuclear power. Hydrogen as a fuel can be used to tackle various energy challenges and provides a number of ways to decarbonize sectors such as transport, the chemical industry, and the steel industry. This paper aims to assess the potential of hydrogen to serve as an economically viable alternative to fossil fuels. Hydrogen's physical properties play an important role in assessing its potential, as well as its advantages and disadvantages in hydrogen combustion and fuel cell propulsion systems. This paper also discusses various challenges related to the storage, transmission, and distribution of hydrogen.
Keywords: Hydrogen Energy; Clean Fuel; GHG Emissions; Fuel Cell; Climate Change.

EFFECTS OF INTERNAL CONTROL ON FINANCIAL MANAGEMENT: A STUDY ON GOMBE STATE

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Abstract
This study examines the influence of internal control on financial management in the Gombe State Ministry of Finance using a survey research design. The population comprised 638 staff members, while a sample size of 246 was determined using Taro Yamane's formula and selected through stratified random sampling. Primary data were collected through structured questionnaires, and analysis was conducted using multiple regression analyses using SPSS. The findings of the study revealed that control environment, risk assessment, control activities, and monitoring and evaluation have positive and significant effects on financial management, with monitoring having the strongest influence. The study concludes that effective internal control systems enhance accountability, transparency, and efficient utilization of public funds. The study therefore, recommended that the Finance Ministry should strengthen control environment, improve risk assessment practices, enforce control activities, and enhance monitoring mechanisms to achieve better financial management outcomes. Additionally, they should ensure strict compliance with financial regulations and provide continuous training for staff to improve internal control effectiveness.
Keywords: internal control, financial management, risk, monitoring, evaluation

1. Introduction

Financial management has increasingly become a central concern in both public and private sector organizations. Particularly as governments strive to ensure efficient allocation, utilization, and accountability of scarce financial resources. In contemporary public administration, effective financial management is not merely about budgeting and expenditure but extends to ensuring transparency, fiscal discipline, and value-for-money in service delivery (Yusuf et al., 2021). More so, the growing complexity of financial transactions, coupled with heightened public demand for accountability, has made financial management systems more vulnerable to inefficiencies, misappropriation, and fraud if not properly controlled (World Bank, 2022). Similarly, scholars have argued that weak financial management practices are often linked to poor governance outcomes, especially in developing economies where institutional frameworks are still evolving and strengthening financial management has become a global priority, particularly through the integration of robust internal control mechanisms (Adeyemi & Olarewaju, 2019).

Financial management effectiveness is fundamentally influenced by the quality of internal control systems embedded within organizations which is seen as a systematic process designed to provide reasonable assurance regarding the achievement of organizational objectives in areas such as financial reporting, operational efficiency, and regulatory compliance (Committee of Sponsoring Organizations of the Treadway Commission, (COSO, 2017)). In the same vein, the components of internal control namely control environment, risk assessment, control activities, and monitoring serve as critical drivers of financial discipline and accountability. Empirical evidence from both developed and emerging economies suggests that organizations with strong internal control systems tend to exhibit better financial management outcomes, reduced incidences of fraud, and improved decision-making processes however, the effectiveness of these components often varies across institutional contexts, thereby necessitating context-specific investigations (Lannoye, 2020).

Furthermore, the significance of financial management is further underscored by the increasing emphasis on public financial management reforms across countries while governments and international development agencies have consistently advocated for reforms aimed at enhancing fiscal transparency, improving budgetary control, and strengthening internal audit systems (Olaoye & Adekanbi, 2020). For instance, the International Monetary Fund (2021) highlights that weak internal control structures remain a major impediment to effective financial management in many developing countries. Additionally, studies have shown that inadequate risk assessment mechanisms and weak monitoring frameworks often lead to budget overruns, leakages, and inefficient resource utilization and thus, the integration of strong internal control components is increasingly viewed as a prerequisite for achieving sound financial management practices (Hassan et al., 2022).

Financial management within the public sector in Nigeria has faced significant challenges over the years, ranging from mismanagement of public funds to weak accountability structures, including the introduction of financial regulations and audit frameworks, issues such as budget indiscipline, delayed financial reporting, and financial irregularities persist (Central Bank of Nigeria CBN, 2022). Moreover, the effectiveness of financial management in Nigeria has been closely linked to the strength of internal control systems within government institutions. Studies have revealed that deficiencies in control environment such as lack of ethical standards and weak leadership often undermine financial management processes (Ezeani & Oladejo, 2020). In addition, inadequate risk assessment practices have been identified as a major factor contributing to financial leakages and fraud within public institutions (Okpala, 2021). More so, control activities, which encompass authorization procedures, segregation of duties, and approval mechanisms, play a pivotal role in ensuring that financial transactions are properly executed and recorded. However, in many Nigerian public sector organizations, these activities are either poorly implemented or circumvented, thereby compromising financial management effectiveness (Adebayo & Olagunju, 2021). Similarly, monitoring and evaluation mechanisms, particularly internal audit functions, are often weak or under-resourced, limiting their ability to detect and prevent financial irregularities and as a result, despite the existence of formal internal control frameworks, their practical implementation remains a challenge, thereby affecting overall financial management outcomes. However, the challenges of financial management within state ministries are even more pronounced due to limited resources, administrative bottlenecks, and institutional inefficiencies (Oladipo & Akinlo, 2022).

In Gombe State, the Ministry of Finance serves as a critical institution responsible for managing public funds, preparing budgets, and ensuring fiscal accountability. However, circumstantial evidence and preliminary observations suggest that issues such as weak control environment, inadequate risk assessment, ineffective control activities, and poor monitoring systems may be affecting the efficiency of financial management within the Ministries across the country (Ezeani & Oladejo, 2020). Furthermore, the increasing demand for transparency and accountability in the management of public resources in Gombe State has heightened the need for a more robust internal control system. Additionally, the control environment within the Ministry, which includes management philosophy, ethical values, and organizational structure, plays a crucial role in shaping financial management practices, where leadership commitment to accountability is weak, internal controls are likely to be ineffective (Oladipo & Akinlo, 2022). Likewise, risk assessment processes are essential for identifying potential financial risks, including fraud and misallocation of resources; however, the absence of systematic risk evaluation frameworks may expose the Ministry to financial vulnerabilities. In the same vein, control activities such as proper authorization and segregation of duties are necessary to ensure the integrity of financial transactions, yet their effectiveness depends largely on adherence to established procedures.

Moreover, monitoring and evaluation, particularly through internal audit functions, are vital for ensuring continuous assessment and improvement of internal control systems (Ezeani & Oladejo, 2020). Despite the acknowledged importance of internal control in enhancing financial management, existing studies in Nigeria have largely focused on federal institutions and private sector organizations, with limited attention given to state-level ministries such as the Gombe State Ministry of Finance. Furthermore, many of these studies tend to examine internal control as a single construct rather than disaggregating it into its core components, thereby limiting the depth of analysis. More importantly, the dynamic nature of public financial management, especially in the face of evolving governance challenges, necessitates updated empirical investigations that reflect current realities. Therefore, this study seeks to examine the

effects of internal control components control environment, risk assessment, control activities, and monitoring and evaluation on financial management in the Gombe State Ministry of Finance.
Thus, this study has the following hypotheses to guide the study.
H_{01}: Control environment has no significant effect on financial management in the Gombe State Ministry of Finance.
H_{02}: Risk assessment has no significant influence on financial management in the Gombe State Ministry of Finance.
H_{03}: Control activities have no significant effect on financial management in the Gombe State Ministry of Finance.
H_{04}: Monitoring and evaluation have no significant effect on financial management in the Gombe State Ministry of Finance.

2. Literature Review

This study review presents conceptualization of key concepts used in the study, drawing from scholarly and institutional perspectives as follows in the subsections below.

2.1 Financial Management

Financial management has been widely defined by scholars as a critical function in ensuring the effective planning, allocation, and control of financial resources within an organization. Brigham and Ehrhardt (2020) defined financial management as the process of planning, organizing, directing, and controlling financial resources to achieve organizational objectives efficiently. Pandey (2021) viewed financial management as a strategic function concerned with the efficient procurement and utilization of funds in order to maximize organizational value. Similarly, Gitman et al. (2019) described financial management as the management of funds to ensure sustainability and profitability of an organization.
In addition, Olaoye and Adekanbi (2020) defined financial management from a public sector perspective as the effective planning, control, and monitoring of public funds to ensure transparency and accountability in government operations. Okoye and Akenbor (2019) described financial management as the systematic process of managing financial resources in a manner that enhances organizational performance. Likewise, Ezeani (2020) viewed financial management as a function that ensures proper accountability and control of financial resources in public institutions. Furthermore, Izedonmi and Ibadin (2019) defined financial management as the process of ensuring that financial resources are used efficiently to achieve organizational goals. Olatunji (2021) described financial management as the effective coordination and control of financial activities within an organization. Therefore, financial management regarded as the planning and controlling of financial resources to ensure optimal performance and sustainability.

2.2 Internal Control

Internal control has been extensively defined in accounting and auditing literature as a fundamental mechanism for ensuring accountability, safeguarding assets, and enhancing organizational efficiency. Committee of Sponsoring Organizations of the Treadway Commission (2017) defined internal control as a process effected by an entity's board of directors, management, and other personnel, designed to provide reasonable assurance regarding the achievement of objectives relating to operations, reporting, and compliance. Similarly, Arens et al. (2020) viewed internal control as a system consisting of policies and procedures established to ensure reliable financial reporting and compliance with laws and regulations.
However, Olaoye and Adekanbi (2020) defined internal control as a process that enhances financial discipline and ensures efficient utilization of public funds. Oladipo and Akinlo (2022) viewed internal control as a monitoring framework used to evaluate financial performance and detect irregularities in public sector organizations. In the same vein, Yusuf, Bello, and Mohammed (2021) described internal control as a system of checks and balances that promotes accountability and efficiency in government institutions. Additionally, Kaplan and Atkinson (2018) defined internal control as a management tool used to ensure that organizational activities align with strategic objectives. Horngren, Sundem, and Stratton (2018) viewed internal control as a system designed to ensure the integrity of financial information and efficient use of resources. Drury (2020) described internal control as a set of procedures and processes that facilitate effective cost control and operational efficiency while Anthony and Govindarajan (2019) defined internal control as a system used by management to influence members of

the organization to implement strategies effectively. Thus, internal control is viewed as a system of rules and procedures designed to ensure that organizational activities are carried out as intended.

2.3 Control Environment

Control environment is widely regarded as the foundation of an effective internal control system, as it sets the tone for organizational behavior and influences the effectiveness of other control components. Committee of Sponsoring Organizations of the Treadway Commission (2017) defined control environment as the set of standards, processes, and structures that provide the basis for carrying out internal control across an organization. Similarly, Arens et al. (2020) viewed control environment as the overall attitude, awareness, and actions of management regarding the importance of internal control.

On the other hand, Oladipo and Akinlo (2022) defined control environment as the foundation for effective monitoring and control of financial activities within government agencies. Yusuf, Bello, and Mohammed (2021) viewed control environment as a set of organizational values and leadership practices that enhance accountability and efficiency in public institutions. In the same vein, Adebayo and Olagunju (2021) described control environment as the structural and ethical framework that supports the implementation of internal control systems. Additionally, Anthony and Govindarajan (2019) defined control environment as a system through which management influences organizational members to achieve strategic objectives. Simons (2019) viewed control environment as a framework of rules, values, and procedures that guide organizational behavior. Drury (2020) described control environment as a managerial control system that ensures efficiency in operations and financial discipline. Finally, Horngren, Sundem, and Stratton (2018) defined control environment as a system that integrates organizational structure, authority, and responsibility to enhance control effectiveness. So, control environment is considered as a governance structure that supports financial accountability and decision-making processes.

2.4 Risk Assessment

Risk assessment is a fundamental component of internal control that involves identifying, analyzing, and managing potential risks that may hinder the achievement of organizational objectives, particularly in financial management. Committee of Sponsoring Organizations of the Treadway Commission (2017) defined risk assessment as the dynamic and iterative process for identifying and analyzing risks to achieving objectives, forming a basis for determining how risks should be managed. Similarly, Kaplan and Mikes (2018) viewed risk assessment as a structured approach to identifying uncertainties and evaluating their potential impact on organizational performance.

Oladipo and Akinlo (2022) posit that risk assessment is a framework for identifying weaknesses in financial systems and improving accountability in public institutions. Yusuf et al. (2021) viewed risk assessment as a process of evaluating financial uncertainties to improve efficiency and transparency in government agencies. In the same vein, Adebayo and Olagunju (2021) described risk assessment as a mechanism for detecting financial vulnerabilities and ensuring proper control measures are implemented. Additionally, Anthony and Govindarajan (2019) defined risk assessment as a system used by management to identify uncertainties and ensure effective strategy implementation. Simons (2019) viewed risk assessment as a process of identifying risks that may affect organizational control systems. Drury (2020) described risk assessment as a managerial process that ensures cost control and financial efficiency by addressing potential risks. Finally, Horngren et al. (2018) defined risk assessment as a process of evaluating uncertainties in financial decision-making. In conclusion, risk assessment is a systematic analysis of risks associated with financial investments and resource allocation.

2.5 Control Activities

Control activities represent a crucial component of internal control systems, as they consist of the policies and procedures established to ensure that management directives are effectively carried out within an organization. Committee of Sponsoring Organizations of the Treadway Commission (2017) defined control activities as actions established through policies and procedures that help ensure management directives to mitigate risks are executed. Similarly, Gelinas et al. (2020) viewed control activities as specific measures designed to ensure that financial transactions are properly authorized, recorded, and reported. More so, Hall (2021) described control activities as operational mechanisms such as approvals, verifications, and reconciliations that are used to ensure the accuracy and reliability

of financial information. In the same vein, Bagranoff et al. (2020) defined control activities as procedures embedded within business processes to safeguard assets and prevent fraud. Granlund (2020) further explained that control activities are managerial actions that ensure compliance with established policies and enhance organizational efficiency.

Similarly, Onipe, Mohammed, and Yahaya (2021) viewed control activities as accountability mechanisms that ensure transparency in government financial operations. Ibrahim and Lawal (2022) described control activities as systematic procedures that enhance financial discipline and prevent mismanagement in public institutions. More so, Adegbie and Fakile (2021) defined control activities as financial control measures aimed at ensuring proper authorization and documentation of transactions. Bassey, Effiong, and Eyo (2020) viewed control activities as operational controls that ensure efficiency and accuracy in financial management processes. Therefore, control activities is a procedure that enhance compliance with internal policies and reduce financial irregularities.

2.6 Monitoring and Evaluation

Monitoring and evaluation constitute a vital component of internal control systems, as they ensure that established controls continue to function effectively and adapt to changing organizational conditions. Committee of Sponsoring Organizations of the Treadway Commission (2017) defined monitoring as ongoing or separate evaluations used to ascertain whether each component of internal control is present and functioning as intended. Similarly, Moeller (2020) viewed monitoring and evaluation as a continuous process of assessing the effectiveness of internal control systems and identifying areas that require improvement. In the same vein, Pickett (2021) defined monitoring and evaluation as mechanisms used to assess internal control performance and ensure that corrective actions are taken where necessary. Alzeban (2020) further explained that monitoring involves the continuous assessment of internal audit functions to enhance accountability and financial discipline.

Furthermore, Lawal and Olatunji (2022) viewed monitoring and evaluation as processes that enhance accountability by ensuring that financial activities are properly reviewed and reported. In the same vein, Yakubu and Salisu (2021) described monitoring as a mechanism for ensuring compliance with financial regulations and minimizing fraud in public institutions. Arena and Azzone (2021) looked monitoring and evaluation as processes that ensure internal control systems remain effective over time through regular reviews and feedback mechanisms. Similarly, Christopher (2021) viewed monitoring as a structured approach to evaluating the effectiveness of governance and control systems within organizations. Sarens and De Beelde (2020) described monitoring as a process that strengthens internal audit effectiveness and improves financial oversight. Merchant and Van der Stede (2021) described monitoring as a process that ensures employees adhere to organizational policies and performance standards. Thus, monitoring and evaluation viewed as a mechanism that enhance financial discipline and ensure proper utilization of resources.

2.7 Empirical Review

Olowookere et al. (2021) carried out a study titled Internal Control Mechanisms and Financial Management in Nigerian Public Sector Organizations. The study employed a descriptive survey design with a population of public sector employees across selected ministries. A sample of 200 respondents was selected using stratified sampling techniques. Primary data were obtained through questionnaires and analyzed using Pearson correlation and regression analysis. The results indicated that control activities and monitoring mechanisms significantly influence financial management efficiency, while risk assessment contributes to reducing financial irregularities. The study emphasized that strong internal control systems are essential for improving financial reporting and accountability.

Abubakar et al. (2022) investigated Effect of Internal Control System on Financial Performance of State-Owned Enterprises in Nigeria. The study adopted a cross-sectional research design and targeted employees of selected state-owned enterprises. A sample size of 180 respondents was determined using Yamane's formula, while purposive and random sampling techniques were employed. Data were collected using questionnaires and analyzed using multiple regression and ANOVA techniques. The findings showed that control environment and control activities significantly influence financial performance; while monitoring and risk assessment play complementary roles in enhancing financial management outcomes. The study concluded that internal control systems are critical drivers of financial efficiency in public institutions.

Usman et al. (2023) conducted a study on Internal Control and Financial Management Practices in Public Sector Ministries in Northern Nigeria. The study adopted a descriptive survey design with a population comprising staff of selected ministries. A sample size of 150 respondents was selected using simple random sampling. Data were collected through structured questionnaires and analyzed using SPSS with regression and correlation analysis. The findings revealed that risk assessment and monitoring significantly affect financial management, while control activities ensure proper execution of financial transactions. The study further indicated that weak control environment negatively impacts financial management effectiveness.

Sule et al. (2024) examined Internal Control Systems and Public Sector Financial Efficiency in Nigeria. The study utilized a quantitative research design and focused on federal and state institutions. The population consisted of finance and audit staff, from which a sample size of 210 respondents was selected using stratified random sampling. Data were collected through questionnaires and analyzed using multiple regression and structural equation modeling (SEM). The findings showed that all internal control components control environment, risk assessment, control activities, and monitoring have a significant positive relationship with financial efficiency. The study concluded that strengthening internal control systems enhances transparency, accountability, and effective financial management in public sector organizations.

Adamu et al. (2020) examined Internal Control System and Financial Accountability in Nigerian State Ministries. The study adopted a descriptive survey design and focused on selected ministries across Northern Nigeria. The population consisted of finance and audit staff, from which a sample size of 140 respondents was drawn using stratified random sampling. Primary data were collected through structured questionnaires, while analysis was conducted using descriptive statistics and multiple regression analysis. The findings revealed that control environment and monitoring had significant positive effects on financial accountability, while risk assessment contributed moderately to improving financial discipline. The study concluded that strengthening internal control components enhances transparency and reduces financial mismanagement in public institutions.

Garba et al. (2021) carried out a study titled Internal Control and Financial Performance of Public Sector Organizations in Nigeria. The study employed a cross-sectional survey design and targeted employees in finance-related departments. A sample size of 175 respondents was selected using simple random sampling techniques. Data were collected using questionnaires and analyzed with correlation and regression techniques. The findings indicated that control activities and risk assessment significantly influence financial performance, while monitoring plays a key role in detecting and preventing financial irregularities. The study further established that weak control environments negatively affect financial management outcomes.

Ahmed et al. (2022) investigated Internal Control System and Public Financial Management in Selected Government Agencies in Nigeria. The study adopted a quantitative research design with a population of government employees across selected agencies. A sample size of 160 respondents was determined using Taro Yamane's formula, and systematic sampling was applied. Data were collected through questionnaires and analyzed using SPSS with regression and ANOVA techniques. The findings showed that risk assessment and control activities have a strong positive impact on financial management; while monitoring and evaluation enhances accountability and efficiency. The study concluded that effective internal control systems significantly improve financial management practices.

Bello et al. (2023) conducted a study on Effect of Internal Control Components on Financial Management in Nigerian Public Sector. The study adopted a survey research design and focused on ministries and parastatals. The population included finance officers and auditors, with a sample size of 190 respondents selected using stratified sampling techniques. Data were collected through structured questionnaires and analyzed using multiple regression analysis. The findings revealed that control environment, control activities, and monitoring significantly affect financial management, while risk assessment plays a preventive role in reducing financial risks. The study emphasized the importance of integrating all control components to achieve effective financial management.

Ibrahim et al. (2024) examined Internal Control System and Financial Efficiency in State-Owned Institutions in Nigeria. The study employed a descriptive and explanatory research design with a population of finance and audit staff. A sample size of 220 respondents was selected using cluster and random sampling techniques. Data were collected through questionnaires and analyzed using structural equation modeling (SEM) and regression analysis. The findings showed that all internal control

components control environment, risk assessment, control activities, and monitoring have a significant positive relationship with financial efficiency. The study concluded that effective implementation of internal control systems leads to improved financial management, enhanced accountability, and better resource utilization in public sector institutions.

Ofei et al. (2020) examined Internal Control Practices and Financial Performance of Banks in Ghana. The study adopted a quantitative survey design with a population of employees from selected banks. A sample size of 154 respondents was selected using simple random sampling. Data were collected through structured questionnaires and analyzed using correlation and multiple regression techniques. The findings revealed that internal control components such as monitoring and risk assessment have a significant positive relationship with financial performance, while control environment showed a weaker influence. The study concluded that effective internal control systems improve financial management outcomes in financial institutions.

Olaoye et al. (2021) investigated Financial Control Practices and Accountability in the Nigerian Public Sector. The study employed a cross-sectional survey design with a population of civil servants in finance departments. A sample size of 337 respondents was determined using Taro Yamane's formula, while stratified sampling was adopted. Data were collected through questionnaires and analyzed using SPSS regression analysis. The findings indicated that internal control practices significantly influence financial accountability and management, with control activities and monitoring showing the strongest effects. The study concluded that effective internal control enhances financial discipline in the public sector.

Abdullahi et al. (2022) conducted a study on Internal Control System and Financial Management in Nigerian Public Institutions. The study adopted a descriptive survey design with a population of staff in selected ministries. A sample size of 180 respondents was selected using simple random sampling. Data were collected through questionnaires and analyzed using Pearson correlation and multiple regression analysis. The findings showed that control environment, risk assessment, and monitoring have significant positive relationships with financial management, while control activities ensure proper execution of financial transactions. The study emphasized that internal control is a key determinant of financial management efficiency.

Olayisade et al. (2023) examined Internal Control System and Financial Management in Federal Government Hospitals in Nigeria. The study used a descriptive research design with a population of hospital staff involved in financial operations. A sample size of 91 respondents was selected using purposive sampling techniques. Data were collected through questionnaires and analyzed using correlation and regression analysis. The findings revealed that all internal control components control environment, risk assessment, control activities, and monitoring have a significant positive relationship with financial management. The study concluded that strong internal control systems improve financial planning and accountability.

Usman et al. (2024) investigated Internal Control and Financial Management Practices in State Ministries in Northern Nigeria. The study adopted a survey research design with a population of ministry staff. A sample size of 150 respondents was selected using simple random sampling. Data were collected through structured questionnaires and analyzed using SPSS regression techniques. The findings indicated that risk assessment and monitoring significantly influence financial management, while control activities improve the accuracy and reliability of financial transactions. The study concluded that internal control systems are essential for improving financial management in public institutions.

Kipaalu et al. (2025) examined Internal Control System and Public Funds Management in Local Governments in Uganda. The study adopted a mixed-method research design with a population of 478 respondents, including finance staff and administrators. A sample size of 381 respondents was selected using Yamane's formula and purposive sampling. Data were collected through questionnaires and interviews, while analysis was conducted using structural equation modeling (SEM) and thematic analysis. The findings revealed that all internal control components control environment, risk assessment, control activities, and monitoring have a significant positive relationship with financial management and public funds utilization. The study concluded that strengthening internal control systems enhances accountability and financial efficiency.

Alzeban (2020) examined The Impact of Internal Audit Effectiveness on Financial Management in Public Sector Organizations in Saudi Arabia. The study adopted a quantitative survey design with a population of internal auditors in government institutions. A sample size of 120 respondents was

selected using simple random sampling. Data were collected through structured questionnaires and analyzed using multiple regression analysis. The findings revealed that monitoring (internal audit effectiveness) has a strong positive and significant relationship with financial management, while control environment enhances accountability. The study concluded that effective internal control systems improve transparency and financial discipline in public sector organizations.

Putri et al. (2021) investigated Internal Control Systems and Financial Accountability in Indonesian Local Governments. The study employed a descriptive survey research design with a population of finance officers in local governments. A sample size of 210 respondents was selected using stratified sampling techniques. Data were collected through questionnaires and analyzed using Structural Equation Modeling (SEM). The findings showed that control activities and risk assessment significantly influence financial accountability and management, while monitoring strengthens financial reporting quality. The study concluded that internal control components collectively enhance financial management efficiency in public institutions.

Mwangi et al. (2022) conducted a study on Internal Control Systems and Financial Performance of County Governments in Kenya. The study adopted a cross-sectional research design with a population of county government staff. A sample size of 180 respondents was selected using simple random sampling. Data were collected through questionnaires and analyzed using correlation and regression analysis. The findings indicated that control environment and monitoring have significant positive effects on financial management, while risk assessment helps in minimizing financial irregularities. The study concluded that strong internal control systems improve financial performance and accountability in government institutions.

Nguyen et al. (2023) examined Internal Control and Financial Management Efficiency in Public Sector Organizations in Vietnam. The study employed a quantitative research design with a population of finance and audit staff in public agencies. A sample size of 165 respondents was selected using purposive and random sampling techniques. Data were collected through questionnaires and analyzed using multiple regression analysis. The findings revealed that control activities and monitoring significantly improve financial management efficiency, while risk assessment enhances financial planning and decision-making. The study concluded that internal control systems play a vital role in strengthening financial management in developing economies.

Smith et al. (2024) investigated Internal Control Systems and Financial Accountability in Public Sector Organizations in the United Kingdom. The study adopted a survey research design with a population of public sector financial managers. A sample size of 200 respondents was selected using stratified sampling techniques. Data were collected through questionnaires and analyzed using regression and ANOVA techniques. The findings showed that all internal control components control environment, risk assessment, control activities, and monitoring have a significant positive relationship with financial management and accountability. The study concluded that effective internal control systems enhance financial transparency and reduce the risk of mismanagement in public institutions.

2.8 Theoretical Review

This study is underpinned by Resource Based View Theory RBV. The Resource-Based View (RBV) theory was propounded by Jay B. Barney (1991), building on earlier contributions by Wernerfelt (1984). The theory posits that the performance and effectiveness of an organization are largely determined by its internal resources and capabilities rather than external factors. According to Barney (1991), for resources to provide sustained advantage, they must be valuable, rare, inimitable, and non-substitutable (VRIN). These characteristics enable organizations to achieve superior performance when such resources are effectively deployed. Similarly, Peteraf (1993) emphasized that organizational success depends on the efficient utilization of internal capabilities that competitors cannot easily replicate. The fundamental assumptions of RBV are centered on resource heterogeneity and resource immobility. Resource heterogeneity implies that organizations possess different bundles of resources, which lead to variations in performance outcomes (Barney, 1991). Resource immobility suggests that certain strategic resources are not easily transferable across organizations, thereby sustaining competitive advantage (Wernerfelt, 1984). More so, Grant (1996) argued that internal capabilities such as systems, processes, and managerial competencies play a critical role in enhancing organizational efficiency. These scholarly contributions reinforce the argument that internal systems, including internal control mechanisms, play a significant role in determining organizational effectiveness.

3. Methodology

This study is quantitative study that adopted survey research design. The population of the study comprised 638 staff members, while a sample size of 246 was determined using Taro Yamane's formula and selected through stratified random sampling. Data were collected through a structured questionnaire designed based on the study variables. The questionnaire is divided into two sections: Section A: Demographic information and Section B: Variables (Internal Control & Financial Management) the Likert scale (1–5) is used: Strongly Disagree (1); Disagree (2); Neutral (3); Agree (4) and Strongly Agree (5), and analysis was conducted to achieve multiple regression analyses using SPSS version 23. The model for the study is specified as:

$$FM=\beta_0+\beta_1 CE+\beta_2 RA+\beta_3 CA+\beta_4 ME+\varepsilon$$

Where:
FM = Financial Management
CE = Control Environment
RA = Risk Assessment
CA = Control Activities
ME = Monitoring & Evaluation
β_0 = Constant
β_1–β_4 = Coefficients
ε = Error term

4. Result and Discussion

4.1 Response Rate

A total of 246 questionnaires were distributed to staff of the Gombe State Ministry of Finance, out of which 228 were returned and valid, representing a 92.7% response rate.

Table 4.1: Response Rate

Description	Frequency	Percentage (%)
Questionnaires Distributed	246	100
Questionnaires Returned	228	92.7
Not Returned	18	7.3
Total	**246**	**100**

Source: Field Survey, (2026).

The table presents the response rate of the questionnaire administered to staff of the Gombe State Ministry of Finance. A total of 246 questionnaires were distributed to respondents, out of which 228 were successfully completed and returned, representing 92.7% of the total distributed. However, 18 questionnaires, accounting for 7.3%, were not returned. The high response rate of 92.7% indicates a strong level of participation and cooperation from the respondents, which enhances the reliability and validity of the data collected. Furthermore, such a high return rate reduces the likelihood of non-response bias and ensures that the findings of the study are representative of the target population. Therefore, the data obtained from the returned questionnaires is considered adequate and suitable for further statistical analysis and generalization of results.

4.2 Descriptive Statistics

This section presents the descriptive analysis of the study variables, namely control environment, risk assessment, control activities, monitoring and evaluation, and financial management. The analysis is based on the mean and standard deviation of respondents' responses, which provide insight into the general perception and level of agreement on each variable. A mean score above 3.0 indicates agreement, while a score below 3.0 indicates disagreement.

Table 4.2: Descriptive Statistics of Variables

Variable	Mean	Std. Deviation
Control Environment (CE)	4.12	0.68
Risk Assessment (RA)	4.05	0.71
Control Activities (CA)	4.20	0.65
Monitoring & Evaluation (ME)	4.18	0.67
Financial Management (FM)	4.22	0.63

Source: SPSS Output, (2026)

The descriptive statistics presented in Table 4.3 shows that the result of control environment (CE) recorded a mean score of 4.12 with a standard deviation of 0.68. This high mean value indicates that respondents generally agree that the Ministry operates within a sound control environment characterized by strong ethical standards, effective leadership, and a clearly defined organizational structure. The control environment serves as the foundation upon which other internal control components are built, and the high level of agreement suggests that management demonstrates commitment to integrity, accountability, and adherence to financial regulations. Furthermore, the relatively low standard deviation implies that respondents' views are consistent, indicating a shared perception regarding the effectiveness of the control environment within the Ministry. This finding suggests that the Ministry has established a supportive governance structure that promotes discipline in financial management.

However, risk assessment (RA) has a mean score of 4.05 and a standard deviation of 0.71. This indicates that respondents agree that the Ministry actively identifies and evaluates financial risks that may affect its operations. Risk assessment is a critical component of internal control, as it enables organizations to anticipate potential threats and implement appropriate measures to mitigate them. The relatively high mean value suggests that risk management practices are reasonably effective within the Ministry, particularly in identifying fraud risks and financial uncertainties. However, the slightly higher standard deviation compared to other variables indicates a moderate variation in responses, which may suggest that some departments or units within the Ministry may not be equally effective in implementing risk assessment procedures. Nevertheless, the overall result reflects a positive perception of risk assessment practices and their contribution to financial management.

Control activities (CA) recorded a mean score of 4.20 with a standard deviation of 0.65, indicating a high level of agreement among respondents. This suggests that key control procedures such as authorization, segregation of duties, approval processes, and proper documentation of financial transactions are effectively implemented within the Ministry. Control activities are essential in ensuring that financial operations are carried out in accordance with established policies and procedures. The high mean value implies that these mechanisms are functioning effectively to prevent errors, fraud, and irregularities in financial transactions. Additionally, the relatively low standard deviation indicates a high level of consistency in responses, suggesting that these control measures are uniformly applied across different departments. This makes control activities one of the strongest internal control components influencing financial management in the Ministry.

On the other hand, monitoring and evaluation (ME) recorded a mean score of 4.18 with a standard deviation of 0.67. This indicates that respondents generally agree that there is effective monitoring of financial activities within the Ministry. Monitoring involves continuous assessment of internal control systems to ensure that they are functioning as intended. The high mean value suggests that internal audit functions, supervision, and performance reviews are actively carried out, thereby enhancing accountability and transparency. Furthermore, the relatively low standard deviation indicates that respondents share similar views regarding the effectiveness of monitoring mechanisms. This implies that the Ministry has established systems for identifying and correcting control deficiencies, which contributes significantly to improving financial management practices.

Finally, financial management (FM), which is the dependent variable, recorded the highest mean score of 4.22 with a standard deviation of 0.63. This indicates that respondents strongly agree that financial management practices within the Ministry are effective. Specifically, the results suggest that financial resources are efficiently utilized, financial reports are accurate and timely, and there is a high level of

accountability in the management of public funds. The low standard deviation further indicates a strong consensus among respondents, suggesting that the perception of financial management effectiveness is widely shared across the Ministry. This finding reinforces the argument that strong internal control systems contribute positively to financial management outcomes.

4.3 Regression Analysis

This section presents the results of the multiple regression analysis.

Table 4.3 Model Summary

R	R^2	Adjusted R^2	Std. Error of Estimate
0.842	0.709	0.701	0.421

Source: SPSS Output, (2026).

The Model Summary table shows that the correlation coefficient (R) is 0.842, indicating a strong relationship between the independent variables and financial management. The coefficient of determination (R^2) is 0.709, which implies that 70.9% of the variation in financial management is explained by control environment, risk assessment, control activities, and monitoring and evaluation. The Adjusted R^2 of 0.701 further confirms that the model is a good fit, while the remaining 29.1% of variation is explained by other factors not included in the model. The standard error of estimate (0.421) indicates a relatively low level of prediction error.

4.4 Regression Coefficient

Table 4.4 Regression Coefficient

Variable	B	Std. Error	Beta	t-value	Sig.
Constant	0.512	0.244	—	2.10	0.037
Control Environment (CE)	0.210	0.061	0.215	3.45	0.001
Risk Assessment (RA)	0.185	0.060	0.198	3.10	0.002
Control Activities (CA)	0.245	0.059	0.263	4.12	0.000
Monitoring & Evaluation (ME)	0.278	0.060	0.289	4.65	0.000

Source: SPSS Output, (2026).

The regression coefficients table provides insight into the individual contributions of each independent variable to financial management. The constant value of 0.512 indicates the level of financial management when all independent variables are held constant. The coefficient for control environment (CE) is 0.210, with a p-value of 0.001, indicating a positive and statistically significant effect on financial management. This implies that an improvement in control environment leads to an increase in financial management efficiency. Similarly, risk assessment (RA) has a coefficient of 0.185 with a p-value of 0.002, indicating that it also has a positive and significant effect on financial management. This suggests that effective identification and management of financial risks contribute to improved financial performance.

Furthermore, control activities (CA) recorded a coefficient of 0.245 with a p-value of 0.000, indicating a strong positive and significant effect on financial management. This implies that proper implementation of control procedures such as authorization and segregation of duties enhances financial accountability. In addition, monitoring and evaluation (ME) has the highest coefficient of 0.278 with a p-value of 0.000, indicating that it has the strongest influence on financial management among the independent variables. This suggests that continuous monitoring, internal auditing, and evaluation mechanisms play a crucial role in improving financial management outcomes.

4.5 Hypotheses Testing

The hypotheses are tested using the results from the regression analysis. The decision rule is to reject the null hypothesis (H_0) if the p-value is less than 0.05 ($p < 0.05$), otherwise accept the null hypothesis.

The results of the hypothesis testing indicate that all the independent variables have statistically significant effects on financial management in the Gombe State Ministry of Finance.

Specifically, for Hypothesis One (H_{01}), the result shows a t-value of 3.45 and a p-value of 0.001, which is less than the 0.05 level of significance. Therefore, the null hypothesis is rejected, implying that control environment has a significant effect on financial management. This suggests that ethical standards, management integrity, and organizational structure play an important role in enhancing financial management outcomes. For Hypothesis Two (H_{02}), the t-value is 3.10 with a p-value of 0.002, which is also less than 0.05. Consequently, the null hypothesis is rejected, indicating that risk assessment has a significant effect on financial management. This implies that effective identification and management of financial risks contribute positively to financial efficiency and accountability. Similarly, for Hypothesis Three (H_{03}), the results show a t-value of 4.12 and a p-value of 0.000. Since the p-value is less than 0.05, the null hypothesis is rejected. This indicates that control activities have a significant effect on financial management. This finding highlights the importance of procedures such as authorization, segregation of duties, and proper documentation in ensuring financial discipline. Furthermore, for Hypothesis Four (H_{04}), the t-value is 4.65 with a p-value of 0.000, which is also below the 0.05 threshold. Therefore, the null hypothesis is rejected, indicating that monitoring and evaluation have a significant effect on financial management. This suggests that continuous supervision, internal audits, and performance reviews are critical in enhancing accountability and improving financial management outcomes.

4.6 Discussion of the Findings

The findings of this study reveal that internal control components—control environment, risk assessment, control activities, and monitoring and evaluation—have significant positive effects on financial management in the Gombe State Ministry of Finance. Specifically, the study found that control environment has a significant positive effect on financial management. This suggests that ethical standards, management integrity, and a well-defined organizational structure play a crucial role in promoting financial discipline and accountability. This finding is in line with the study of Ezeani and Oladejo (2020), who reported that a strong control environment enhances financial transparency in public sector institutions. Similarly, Arens, Elder, and Beasley (2020) emphasized that the control environment sets the tone for effective internal control and influences the behavior of employees in financial management processes. Furthermore, the study revealed that risk assessment significantly influences financial management. This indicates that the ability of the Ministry to identify, evaluate, and manage financial risks contributes to improved financial decision-making and prevention of financial irregularities. This finding supports the work of Okpala (2021), who found that effective risk assessment practices reduce the likelihood of fraud and mismanagement in public institutions. In the same vein, Kaplan and Mikes (2018) noted that proactive risk assessment enhances organizational performance by minimizing uncertainties associated with financial operations.

In addition, the findings show that control activities have a strong and significant effect on financial management. This implies that procedures such as authorization, segregation of duties, and proper documentation of financial transactions are essential in ensuring accountability and efficiency in financial operations. This result is consistent with Adebayo and Olagunju (2021), who reported that effective control activities significantly improve financial management in the public sector. Similarly, Romney and Steinbart (2021) argued that control activities reduce the risk of errors and fraud, thereby enhancing the reliability of financial information. Moreover, the study found that monitoring and evaluation have the most significant impact on financial management among all the independent variables. This suggests that continuous supervision, internal audits, and performance reviews play a critical role in ensuring that financial management systems function effectively. This finding aligns with Oladipo and Akinlo (2022), who emphasized that monitoring mechanisms enhance accountability and reduce financial irregularities in public sector organizations. Similarly, Messier, Glover, and Prawitt (2021) noted that effective monitoring ensures the continuous improvement of internal control systems.

5. Conclusion and Recommendation

Based on the findings of this study, this study concluded that internal control plays a critical role in enhancing financial management in the Gombe State Ministry of Finance. Specifically, control environment, risk assessment, control activities, and monitoring and evaluation significantly influence financial management outcomes. In addition, a strong control environment promotes ethical behavior and accountability, while effective risk assessment reduces financial vulnerabilities. The study therefore, recommended that the Finance Ministry should strengthen control environment, improve risk assessment practices, enforce control activities, and enhance monitoring mechanisms to achieve better financial management outcomes. Additionally, they should ensure strict compliance with financial regulations and provide continuous training for staff to improve internal control effectiveness.

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THE PROMPT AS A COMPOSITIONAL DEVICE

UMAN–AI DIALOGUE IN THE EARLY STAGES OF ARCHITECTURAL DESIGN

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ABSTRACT

Artificial intelligence is increasingly influencing the early stages of architectural design, yet its role often remains confined to the rapid production of suggestive images. This study investigates the prompt as a compositional device capable of translating design intentions into spatial configurations, and asks to what extent different linguistic structures influence architectural coherence in recognizable and repeatable ways. A prospective, controlled comparative protocol is applied to the design of a small Mediterranean pavilion intended for meeting, rest, and landscape contemplation. In Experiment 1, a constant functional brief is combined with four prompt orientations (functional, geometric, perceptual, and narrative) and a neutral control condition. Eight independent generations per condition (forty outputs) are anonymised and assessed by a blind panel of architects on eight criteria: spatial hierarchy, circulation, thresholds, geometric coherence, light and climate, materiality, landscape, and developability. Evaluators also attempt to recognise the dominant orientation without seeing the prompt. Experiment 2 compares a single extended prompt with a sequence of specialised prompts applied to the same starting proposal. The analysis does not evaluate artificial intelligence as an autonomous author, but as an interactive medium within a human-led design process. Since generation and expert assessment are still to be completed, the paper presents hypotheses and falsification criteria rather than results, anticipating differentiated profiles across prompt families instead of a universally superior prompt. The study proposes the concept of the prompt as a meta-project: a documented system of instructions, invariants, and criteria that establishes relationships, constraints, and desired experiences before architectural form is defined.

Keywords: artificial intelligence; architectural composition; prompt design; human–AI co-design; generative design.

1. INTRODUCTION

Generative artificial intelligence has entered architectural practice through text-to-image models, multimodal systems, and language-based interfaces capable of producing images, descriptions, layouts, and preliminary digital models. Their main attraction is speed. In a short time, a designer can obtain a broad range of alternatives at a stage when programme, form, and relationship with context are still unstable. This capacity can support divergent exploration, but it also creates a methodological ambiguity: the fluency of representation can be mistaken for the coherence of a project.

Architectural composition cannot be reduced to the production of a stylistically persuasive image. It concerns the ordering of relations between parts and whole, solids and voids, movement and rest, exposure and protection, structure and enclosure, light and material, ground and landscape. A generated image may appear credible while describing an inaccessible entrance, inconsistent spans, unresolved thresholds, contradictory circulation, or a building that cannot be reconstructed coherently in plan and section. The distinction between visual plausibility and architectural validity is therefore central to any critical use of generative systems.

Design research has long described architecture as an iterative process in which the designer frames a problem, proposes a move, observes its consequences, and reformulates both problem and solution. Schön (1983) called this a reflective conversation with the situation, while Lawson (2006) and Cross (2006) emphasised that design knowledge develops through conjecture, representation, evaluation, and revision. Generative AI introduces a probabilistic interlocutor into this process. It can enlarge the field of possible configurations, but it does not independently understand situated need, cultural significance, professional duty, or the consequences of construction.

The prompt is commonly treated as a command or as a recipe for obtaining a desired image. This paper proposes a more precise interpretation. A prompt is a selective representation of the design problem. Like a diagram, model, or sketch, it foregrounds some relations and leaves others in the background. A functional prompt privileges activities, capacities, adjacency, and access; a geometric prompt foregrounds axes, modules, proportions, and invariants; a perceptual prompt emphasises light, shade, material transitions, acoustics, and climate; a narrative prompt organises arrival, orientation, encounter, pause, and departure. These orientations are not independent architectural categories. They are analytical lenses that allow the effect of linguistic emphasis to be studied.

Rule-based generative design has historically relied on explicit grammars, parameters, and evaluation functions. Shape grammars demonstrated that formal alternatives could be generated through declared rules (Stiny & Gips, 1972), while parametric design made dependencies among variables visible and revisable (Oxman, 2017). Contemporary diffusion models differ because the connection between instruction and output is statistical rather than explicitly encoded. Latent diffusion models can generate high-resolution images efficiently from text (Rombach et al., 2022), but visual coherence alone does not establish spatial or technical correctness.

Recent research seeks to connect natural-language requirements with more structured architectural representations. HouseLLM uses a large language model to generate an initial layout that is subsequently refined through a conditional diffusion process (Zong et al., 2024). Text-to-Layout documents a replicable workflow that translates language into native parametric elements suitable for Revit-based drafting (Duggempudi et al., 2025). Other approaches introduce verifiable rewards to improve compliance with topological and numerical constraints (Lara et al., 2026). These studies suggest that language can become a design interface when constraints, outputs, and evaluation procedures are made explicit.

However, a gap remains between systems that generate representations and methods that evaluate architectural composition. Many demonstrations select a limited number of successful images, making it difficult to separate the effect of the prompt from stochastic variation, model bias, or curatorial choice. Without a control condition, repeated generations, blind evaluation, and declared criteria, claims about the architectural influence of prompt structures remain largely impressionistic.

This study therefore asks: to what extent do different prompt structures influence architectural coherence in recognizable and repeatable ways? The first objective is to test whether five prompt conditions generate different profiles across architectural criteria. The second is to determine whether evaluators can recognize the dominant linguistic orientation without seeing the original prompt. The third is to compare one extended prompt with a controlled sequence of specialised prompts. The study does not search for a universal optimal prompt. It proposes a method for investigating how language directs attention and how the architect can retain critical agency within an AI-assisted process.

Three hypotheses guide the protocol. H1 predicts statistically and architecturally meaningful differences among the criterion scores of the five conditions. H2 predicts that correct recognition of the four oriented prompt families will exceed chance level. H3 predicts that sequential prompting will improve design developability without reducing the clarity of the compositional principle. Because the experimental generation and expert assessment are still to be completed, these propositions are presented as hypotheses and not as acquired results.

2. MATERIALS AND METHODS

2.1.Research design

The research adopts a controlled comparative design with two linked experiments. Experiment 1 isolates the linguistic orientation of the prompt while holding the architectural brief and generation settings constant. Experiment 2 compares two prompting workflows: a single extended instruction and a sequence of specialised prompts. The unit of analysis is not the attractiveness of an image but the architectural proposal that can be inferred from the combined visual and textual output.

The protocol is designed as a prospective study. It defines the sample, variables, evaluation criteria, and analysis before the outputs are scored. This distinction is essential because selecting criteria after viewing the generations would increase confirmation bias. All outputs, including weak or contradictory proposals, remain in the dataset unless a technical failure prevents the system from producing a readable

response. Technical exclusions must be documented separately and may not be justified by aesthetic preference.

2.2. Case study and constant brief

The case study is a small, single-storey Mediterranean pavilion located on a hypothetical coastal edge with a gentle slope. The programme includes a sheltered gathering space for approximately twenty people, a quieter area for individual rest, a continuous accessible route, a compact service area, and a controlled relationship with the sea view. The site is assumed to receive intense afternoon solar exposure and summer breezes. The pavilion typology limits programme complexity and makes linguistic effects easier to observe, while still requiring decisions about hierarchy, movement, threshold, climate, material, and landscape.

The constant instruction establishes programme, approximate scale, accessibility, environmental conditions, and the preliminary nature of the output. It does not prescribe a style, named architect, historical reference, or predetermined form. Prompts are kept comparable in length and syntax so that verbosity does not become an uncontrolled variable. The variable component changes only the dominant compositional orientation.

2.3. Prompt conditions and sample

Table 1. Experimental prompt conditions

Condition	Linguistic orientation	Relations foregrounded
Control	Constant brief only	No additional compositional emphasis
Functional	Activities, capacities, adjacency, access	Programme, services, circulation continuity
Geometric	Axes, modules, proportions, solid-void order	Hierarchy, rhythm, formal invariants
Perceptual	Light, shade, climate, material, views	Atmosphere, environmental response, sensory thresholds
Narrative	Arrival, crossing, encounter, pause, departure	Temporal sequence and embodied experience

Source: authors' elaboration.

Eight independent generations are produced for each condition, yielding forty outputs. The number is sufficient for an exploratory comparison while remaining compatible with expert evaluation. Each generation begins from the same constant brief and uses a fresh session or equivalent reset procedure to minimise conversational carry-over. No output is regenerated because it appears unattractive. If the platform offers a seed, it is recorded; if the seed cannot be controlled, this limitation is declared and each generation is treated as an independent stochastic trial.

The output package for each trial contains the generated image or images, the complete textual response where applicable, and a structured description of plan and section. Requiring more than a single perspective reduces the risk of evaluating atmosphere alone. Nevertheless, these materials remain preliminary representations and are not treated as construction documents.

2.4. Generation protocol and documentation

The same model, model version, aspect ratio, resolution, inference settings, and reference-image policy are used across all conditions. The date and time are recorded because model behaviour can change after platform updates. The protocol sheet includes the complete prompt, system and version, seed where available, reference images, file name, anonymous code, and any human intervention. Cropping, colour correction, inpainting, prompt revision, or manual redrawing are prohibited before the blind evaluation. If a platform automatically revises prompts, the revised version is retained when it can be accessed.

The constant base instruction is: Develop a preliminary architectural concept for a small single-storey Mediterranean pavilion on a gently sloping coastal site. Include a sheltered space for approximately twenty people, a quiet area for individual rest, a continuous accessible route, and a compact service zone. Describe the organisation in plan and section, explain the relationship with climate and landscape, identify assumptions that require verification, and do not present the result as ready for construction.

The functional condition adds requirements concerning activities, capacities, adjacency, accessible movement, service efficiency, and the avoidance of residual space. The geometric condition requests a legible axis, modular rhythm, proportional hierarchy, and intentional solid-void system, distinguishing invariants from elements that can respond to site and programme. The perceptual condition translates atmosphere into observable operations concerning light, shade, framed views, breeze, acoustics, texture, and transitions between exposed and protected conditions. The narrative condition organises the project through arrival, compression, orientation, encounter, pause, and departure while retaining functional and accessible movement.

2.5. Participants and blind evaluation

The principal evaluation panel includes at least five architects with design experience. Professional background, years of experience, and familiarity with generative AI are collected for descriptive purposes. A separate student panel may be added as an exploratory comparison, but its scores are not pooled with those of the professional panel. The study should obtain informed consent and avoid collecting unnecessary personal data.

Outputs are anonymised with random codes and presented in a different random order to each evaluator. Neither prompt family nor research hypothesis is disclosed during scoring. Evaluators assess each proposal using a five-point Likert scale, where 1 indicates an absent, contradictory, or unusable relationship and 5 indicates a clear, coherent, and transferable relationship. A short comment field allows evaluators to identify the evidence supporting the score or the contradiction that reduced it.

After scoring, the evaluator assigns the output to one of five recognition categories: functional, geometric, perceptual, narrative, or no recognizable orientation. The control outputs are included in the same sequence. This task tests whether linguistic emphasis leaves an architectural trace visible to independent observers rather than only to the researcher who formulated the prompts.

2.6. Evaluation matrix

Table 2. Architectural evaluation criteria

Criterion	Operational question	Scale
Spatial hierarchy	Is an order between primary and secondary spaces recognizable?	1-5
Circulation	Are access and movement legible, continuous, and accessible?	1-5
Thresholds	Are transitions among open, enclosed, exposed, and protected conditions clear?	1-5
Geometric coherence	Does the proposal maintain a recognizable ordering principle?	1-5
Light and climate	Do orientation, shade, and ventilation respond to the stated context?	1-5
Materiality	Are form, materials, and preliminary construction logic compatible?	1-5
Landscape	Do ground, views, and edges participate in the composition?	1-5
Developability	Can the proposal be translated into plan, section, and technical checks?	1-5

Source: authors' elaboration.

The eight criteria deliberately separate visual appeal from architectural coherence. Spatial hierarchy concerns the relative importance and articulation of spaces. Circulation examines movement rather than the mere presence of paths. Thresholds evaluate transitions and gradients. Geometric coherence concerns the persistence of an ordering principle across the proposal. Light and climate measure environmental response. Materiality examines whether form and construction logic are compatible at a preliminary level. Landscape concerns topography, views, and boundaries. Developability asks whether the proposal contains enough coherent information to support subsequent design work.

Before formal scoring, the evaluation sheet is piloted with two architects not included in the final panel. The pilot checks the clarity of definitions, duration, image scale, and possible redundancy among

criteria. Definitions may be clarified before data collection but cannot be altered after formal scoring begins.

2.7. Data analysis

For each condition and criterion, the analysis reports median, interquartile range, mean, and standard deviation. Medians and non-parametric procedures are prioritised because the scores are ordinal and the planned sample is limited. A Kruskal-Wallis test can explore differences among the five conditions for each criterion. Where an overall difference is observed, corrected pairwise comparisons can identify which conditions differ. Effect sizes and confidence intervals should accompany p-values so that statistical detectability is not confused with architectural relevance.

Inter-rater reliability is assessed using an index appropriate to the final data structure. An intraclass correlation coefficient may be reported for aggregated scale scores when its assumptions are satisfied; Fleiss' kappa is appropriate for the categorical recognition task. Recognition accuracy is compared with chance, with the exact baseline defined according to whether the no-orientation category is included. A confusion matrix identifies systematic overlap, such as perceptual proposals being read as narrative.

Qualitative comments are coded for recurrent strengths, omissions, and contradictions. Codes may include unresolved access, residual space, inconsistent structure, scenic but nonfunctional threshold, environmental responsiveness, or strong formal hierarchy. Quantitative and qualitative evidence are interpreted together. A higher score is meaningful only when the proposal provides identifiable architectural evidence.

2.8. Second experiment: extended prompt versus sequence

The second experiment examines whether prompting works more effectively as a temporal process than as a single container of requirements. One starting proposal is selected using a declared rule based on median scores and absence of technical failure. The same proposal is developed through two paths. Path A uses one extended prompt containing functional, geometric, perceptual, narrative, and critical requirements. Path B uses five consecutive stages: function, geometry, perception, narrative, and critique.

In Path B, each stage records the current proposal and identifies approved invariants. The next prompt must preserve these invariants unless a contradiction is explicitly documented. The critical stage asks the system to compare the proposal with all eight evaluation criteria, identify unsupported assumptions, and list checks required in plan, section, structure, climate, accessibility, and regulation. The final outputs are anonymised and evaluated with the same matrix by reviewers who do not know which workflow produced them.

The comparison focuses on developability, omission rate, contradiction rate, and clarity of the compositional principle. The hypothesis is not that more prompting automatically produces better design. Excessive accumulation can create verbosity, conflicts, and loss of hierarchy. The sequential workflow is expected to be advantageous only if it makes decisions traceable and permits critical interruption.

3. FINDINGS AND DISCUSSION

3.1. Expected findings and falsification criteria

Because the experiment has not yet been completed, this section distinguishes expected patterns from empirical findings. The anticipated result is not a universally superior prompt family but a differentiated profile. Functional prompts are expected to receive relatively higher scores for programme and circulation; geometric prompts for hierarchy and formal coherence; perceptual prompts for light, climate, material transitions, and landscape; and narrative prompts for thresholds and experiential continuity. These expectations define testable predictions, not conclusions.

The control condition is essential. If specialised prompts do not outperform the control on their relevant criteria, the claim that linguistic orientation has a compositional effect must be reduced. If recognition remains at chance level, the families may be too overlapping, the outputs may be dominated by model priors, or the evaluation material may not contain sufficient architectural information. If inter-rater agreement is low, the criteria may require refinement or architectural quality may be too dependent on individual interpretation for the proposed scale.

The hypotheses can also be challenged by trade-offs. A geometric condition may produce a strong principle but weak environmental adaptation; a perceptual condition may produce compelling light and

landscape relations but ambiguous dimensions; a functional condition may be clear yet generic; and a narrative condition may organise experience without maintaining structural or geometric consistency. Such profiles would support the idea that prompt families operate as selective lenses rather than complete design methods.

3.2. The prompt as an attentional device

The central theoretical proposition is that prompts distribute attention. They do not contain a completed building in compressed form. Their influence lies in deciding which relations become explicit enough to be generated, observed, questioned, and revised. This interpretation avoids two opposite errors: treating the model as an autonomous designer and treating the prompt as neutral input. The output emerges from model priors, linguistic framing, stochastic variation, and human selection.

A compositional prompt differs from an evocative prompt. Words such as Mediterranean, open, sustainable, or contemplative can trigger stylistic associations without defining an operation. A more testable instruction links the desired quality to a relation: delay the sea view through a shaded threshold; maintain an accessible continuous path; use a central void to organise adjacency; or modulate section depth to control afternoon sun. Moving from adjective to operation makes the prompt more architecturally discussable.

This does not mean that every design intention must be converted into a numerical constraint. Architecture also involves ambiguity, atmosphere, memory, and cultural interpretation. The protocol instead requires that evaluators identify the spatial evidence through which an intention becomes perceptible. In this way, subjective judgment is not eliminated but made more transparent and comparable.

3.3. From a single prompt to a meta-design process

The term meta-design is used here in a limited sense: a documented sequence of instructions, evaluations, and revisions through which the architect establishes relations, invariants, and criteria before final configuration. A single prompt remains a partial representation. A sequence can progressively define programme, introduce a geometric order, test environmental consequences, organise embodied experience, and expose contradictions.

Sequential prompting differs from simply writing a longer prompt because it separates decisions in time. The architect can observe what each stage changes, decide what should be retained, and stop when the system violates an approved invariant. This traceability is valuable in research, education, and professional practice. It makes authorship legible as the exercise of judgment rather than as the manual production of every image.

However, the sequence should not become a ritual that conceals weak decisions behind procedural complexity. Its value depends on explicit checkpoints and on the possibility of rejection. The model must not be allowed to reinterpret unresolved problems as visually finished solutions. A final critical prompt is therefore insufficient by itself; its observations must be transferred into independent architectural checks.

3.4. Authorship, responsibility, and professional limits

The distribution of roles in AI-assisted design is asymmetrical. The system generates variations from learned statistical regularities. The architect defines the problem, chooses the representation, establishes criteria, recognizes errors, selects, transforms, and verifies. Recording prompts and parameters does not diminish authorship. It documents how authorship is exercised and allows others to reconstruct the decision process.

Generated outputs cannot replace dimensioned plans, coordinated sections, structural reasoning, accessibility verification, energy analysis, cost control, or regulatory assessment. Developability is therefore defined modestly: a proposal is developable when it contains coherent relations that can be translated into subsequent drawings and tests. It is not equivalent to technical feasibility or approval.

The protocol also limits post-generation curation. Architectural publications often show only successful outputs, but selective display can exaggerate model control. Retaining all trials makes stochastic instability visible and prevents the researcher from choosing only images that support the argument. This is particularly important when the research question concerns repeatability.

3.5. Educational and practical implications

In design education, the protocol can help students translate vague aspirations into observable relations. Instead of asking for an open, contextual, or sustainable pavilion, students must specify how openness is graded, how the ground is crossed, how solar exposure is controlled, or how a threshold changes the sequence of movement. Evaluation then focuses on framing and critique rather than on the seduction of the final image.

In practice, the method can support early option generation, client communication, and comparison among alternative priorities. Its usefulness is greatest before major constraints are fixed, when several plausible directions need to be examined. It becomes less reliable when used to imply exact dimensions, compliance, or construction detail without independent modelling and verification.

The method also suggests a research agenda connecting linguistic prompts with spatial graphs, parametric models, and BIM. Natural language could define intentions, while structured representations test adjacency, accessibility, area, structure, and climate. Recent text-to-floorplan and text-to-BIM research points in this direction, but architectural judgment remains necessary to determine which constraints matter and how conflicts should be resolved.

3.6. Limitations

The study uses one typology and a hypothetical site. A small landscape pavilion may privilege perceptual and narrative variables. Generalisation requires additional cases, including an interior, a complex public programme, and a constrained urban site. The planned number of experts is appropriate for an exploratory study but limits inferential strength and subgroup analysis.

Generative models change rapidly and can behave differently after undocumented updates. Recording version and date improves transparency but does not eliminate this instability. The prompt families also overlap because function, geometry, perception, and narrative belong to the same architectural system. The study therefore refers to dominant orientations rather than independent categories.

The evaluation relies on representations rather than inhabited buildings. Reviewers infer movement, atmosphere, and feasibility from images and descriptions. The results will therefore concern represented architectural coherence, not measured performance or post-occupancy experience. Future research should connect the protocol to plan reconstruction, environmental simulation, accessibility checking, physical prototypes, and user evaluation.

4. CONCLUSION AND RECOMMENDATIONS

This paper proposes a controlled method for studying the prompt as a compositional device in the early stages of architectural design. Its contribution is not the claim that one linguistic family is superior. It is the construction of a replicable relationship between prompt structure, generated variation, and architectural evaluation. A constant brief, a control condition, repeated independent generations, blind expert assessment, a recognition task, and complete documentation transform an impressionistic comparison into a testable protocol.

If the hypotheses are confirmed, the prompt can be interpreted as an attentional device and the prompt sequence as one component of a meta-design process. If the expected differences do not emerge, the negative result will be equally relevant. It would show the limits of linguistic control and support the integration of text with spatial graphs, parametric rules, BIM objects, or verifiable constraints.

Five recommendations follow. First, researchers should distinguish generated imagery from validated architectural information. Second, all trials and exclusions should be documented, not only successful images. Third, prompt conditions should include a neutral control and repeated generations. Fourth, architectural evaluation should be blind and should separate visual appeal from hierarchy, circulation, thresholds, climate, materiality, landscape, and developability. Fifth, AI-assisted workflows should end with independent professional verification rather than with a self-critique produced by the same system.

Artificial intelligence can expand the field of alternatives and expose new questions, but it cannot assume architectural responsibility. The architect remains responsible for framing, selecting, transforming, testing, and communicating the project. The value of the system lies not in automating judgment but in producing variations that make priorities and contradictions more visible.

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Research and Author Contributions:
This research was developed within the framework of the departmental research laboratory STRETT-ARCH – Strait Regeneration, Territory Transformation, Architecture of the Department of Architecture and Design (dAeD), Mediterranea University of Reggio Calabria (UNIRC), in which the authors are actively involved. It also forms part of the activities carried out under the international agreement Water's Thresholds: Shaping the Mediterranean Space, established between the dAeD Department and the IKSAD Institute. Although the research was jointly conceived and developed by both authors, responsibility for drafting the manuscript is attributed as follows: the Abstract, Section 1, Section 2.7, and Section 4 were jointly written by C.S.V.A. and A.G.Q.; Sections 2.1, 2.5, 3.1, and 3.5 were written by C.S.V.A.; Sections 2.2, 2.3, 2.4, 2.6, 2.8, 3.2, 3.3, 3.4, and 3.6 were written by A.G.Q. Both authors reviewed and approved the final version of the manuscript.

APPENDIX A. PROMPT SET

Constant instruction: Develop a preliminary architectural concept for a small single-storey Mediterranean pavilion on a gently sloping coastal site. Include a sheltered space for approximately twenty people, a quiet area for individual rest, a continuous accessible route, and a compact service zone. Describe the organisation in plan and section, explain the relationship with climate and landscape, identify assumptions that require verification, and do not present the result as ready for construction.
Functional condition: Prioritise activities, capacities, adjacency, accessibility, service efficiency, and continuity of circulation. Avoid residual spaces. Explain how each part supports use and how visitors move from arrival to the landscape edge.
Geometric condition: Organise the pavilion through a legible axis, modular rhythm, proportional hierarchy, and intentional system of solids and voids. Distinguish invariants from elements that may deform in response to site and programme.
Perceptual condition: Compose the pavilion through gradients of light and shade, filtered views, breeze, acoustic variation, texture, and transitions between exposed and protected conditions. Translate every atmospheric intention into an observable spatial operation.
Narrative condition: Organise the project as a sequence of arrival, compression, orientation, encounter, pause, and departure. Explain how thresholds, changes of scale, and framed views support the sequence while maintaining functional and accessible movement.
Critical verification: Evaluate the proposal in relation to hierarchy, circulation, thresholds, geometric coherence, climate, materiality, landscape, and developability. Identify contradictions, unsupported

assumptions, and aspects requiring verification through plan, section, structure, climate analysis, accessibility, and regulation.

APPENDIX B. MINIMUM RECORDING SHEET

Table 3. Information to be recorded for every generation

Field	Required information
System	Platform, model, and version
Time	Date and time of generation
Input	Complete prompt and reference images
Parameters	Seed, aspect ratio, resolution, and available settings
Output	Anonymous code and original file
Human intervention	Selections, edits, exclusions, and reasons
Evaluation	Scores, recognition category, and reviewer comments

Source: authors' elaboration.

NUMERICAL STUDY OF SOLAR CHIMNEY'S THERMALPERFORMANCE FOR BUILDING VENTILATION

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Abstract
This work is concerned with the numerical investigation of the performance of a natural ventilation system with a solar chimney as a passive technique to enhance the indoor thermal comfort and cut down the energy consumption in a room.
The simulations were performed using ANSYS Fluent 15 and the effects of two main parameters, i.e. solar irradiation and chimney width were investigated. The effects of these factors on the temperature distribution, air speed and flow rate and air change rate (ACH) have been investigated.
The results indicate that the solar radiation is the primary driver of the solar chimney system. The volumetric flow rate is higher, and thus the air renewal rate increases greatly with the intensification of the sun irradiation. Furthermore, the chimney shape, especially the width, has a great impact on the air flow and heat transfer.
Keywords: Solar chimney, Mass flow rate, Natural convection, Passive ventilation, Air change rate.

Introduction

Ventilation has a major role in maintaining interior air quality and thermal comfort in buildings. It encourages air renewal by bringing in fresh air and removing stale air that includes pollutants, excessive moisture, particles, and smells. This process helps regulate interior temperature and humidity while improving hygiene conditions and occupant well-being. In a context where lowering building energy usage and environmental concerns have been key priorities, natural ventilation has emerged as a practical, efficient, and sustainable option. Modern architecture is increasingly using passive technology that can take advantage of regional climate conditions. One of the most promising technologies in these systems is the solar chimney. By utilizing solar energy to provide a thermal buoyant effect, it promotes indoor air renewal without the need for energy-intensive mechanical equipment. Harris and Helwig [1] investigated the effects of solar chimney inclination experimentally and statistically, demonstrating that the inclination angle is a critical component for improving ventilation performance. In an experimental and numerical study of a modified solar chimney, Lal [2] found that an air gap of 60 mm, an inlet opening of 300 mm, and a small glazing inclination improved ventilation performance for the configuration under investigation, with air exchange rates ranging from 2.39 to 7.13 ACH. Shi et al. [3] discovered that a number of factors, including chimney height, air gap, opening size, and inclination angle, had an impact on system performance. Many specific studies have examined the influence of inclination. The inclination angle affects the system's airflow behavior and the quantity of solar energy it receives, according to Mathur et al. [4]. The inclination angle for roof-mounted solar chimneys cannot be considered independently of system orientation and climate, as Kong et al. [5] showed. Furthermore, Xu and Liu [6] investigated the use of a solar chimney for natural ventilation in a Nanjing room. A system with a 45° inclination angle worked the best under the conditions, according to their findings. The authors also highlighted how the airflow rate is influenced by the air gap and the ratio of opening dimensions to chimney height. These results, which are consistent with those reported by Mathur et al. [4] and Kong et al. [5], demonstrate that the optimal inclination angle is highly dependent on the system configuration and the environmental variables taken into consideration. Hosien and Selim [7] have shown that the choice of glazing material may significantly affect system performance. Mohamed et al. [8] conducted a quantitative analysis of the effects of aperture form and placement in a space with a solar chimney. Their results showed that the position of the aperture has a greater impact on ventilation performance than its shape. Huang et al. [9] investigated the effects of several geometric and thermal factors using a validated CFD model. They demonstrated how increasing the absorber temperature and window area might significantly increase the airflow rate, even if expanding the cavity width would have a detrimental effect under the design under consideration. More study has been done on the incorporation of solar chimneys into buildings with many zones or levels. Shi [10] shown the importance of room configuration while studying wall-mounted solar chimneys since the size and arrangement of

the interior space may significantly change the resulting airflow speeds. The importance of zone layout and connection for solar chimney performance in multi-zone structures has been emphasized by Zhang et al. [11]. These findings imply that extrapolating the performance of an isolated solar chimney to a complex structure is not always feasible.
Hussain and Oosthuizen [12] developed a CFD model to assess the efficiency of solar chimney ventilation. Their study also highlighted how geographic location and solar radiation intensity affect ventilation effectiveness. Jiménez-Xamán et al. [13] investigated a roof-mounted solar chimney attached to a single room using a technique that integrated global energy balances and CFD simulations. The results showed higher ventilation rates in both summer and winter, indicating the technology's ability to simultaneously enhance indoor air renewal and temperature conditions. Dhahri and Aouinet [14] emphasized the importance of air temperature, airflow velocity, and solar heat flux in creating thermal comfort conditions.
Ardila et al. [15] stressed the need of considering seasonal and meteorological variations when evaluating solar chimney performance. Nguyen et al. [16] investigated a number of ventilation strategies that combined solar chimneys with a heated wall. Among the configurations analyzed, the parallel arrangement with separate outlets produced the greatest airflow rates, with gains of up to 40% when compared to some reference setups. Moosavi et al. proposed a solar chimney with a water-spray system and a windcatcher [17]. Under the conditions studied, this configuration improved building ventilation and cooling at the same time. Xu et al. [18] investigated a Trombe wall that uses phase change materials (PCMs) to improve thermal stability and natural ventilation. The results suggest that PCM integration may reduce temperature fluctuations and extend the ventilation effect for around an hour after dark. Specifically, the review by Shi et al. [3] confirms the problem's very complex character and highlights the need for more experimental and numerical research under different configurations and climatic conditions. The current study is part of this research context. It aims to assess how well a room's solar chimney-based passive ventilation system works. Particular attention is paid to how the room's thermal behavior and airflow circulation are affected by solar radiation and chimney width.

Materials and Methods

This section describes the physical configuration adopted for the numerical simulation of the solar-chimney ventilation system. The investigated model represents a simple room measuring 2.9 m in length and 3 m in height. A vertical solar chimney is attached to one of the vertical walls of the room. The external face of the chimney is equipped with a transparent glazing panel 3 m in length, creating an air space between the glazing and the absorbing wall. This space forms a vertical air channel with a thickness of 0.1 m, through which air can circulate freely.
The insulation layer located behind the absorbing wall has a thickness of 0.01 m, as does the wall located behind the absorber. The lower opening of the solar chimney has a height of 0.1 m, while a 0.3 m-high window is provided to allow air circulation.

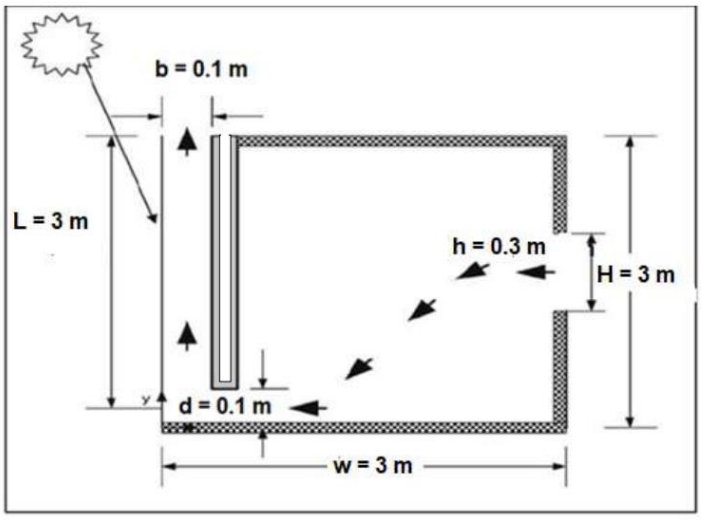


Figure 1. General schematic of the physical domain used in the study.

The mathematical model developed in this study is based on the following simplifying assumptions, which make the problem more tractable while maintaining a realistic representation of the physical phenomenon:

- The flow is assumed to be two-dimensional.
- The working fluid is air, assumed to be viscous, Newtonian, and incompressible, and the Boussinesq approximation is applied [20].

Governing Equations

Mass Conservation Equation (Continuity Equation)

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

with :

u and v are the flow velocity components in the x- and y-directions, respectively.

Momentum Conservation Equations (Navier–Stokes Equations)

$$\rho\left(u\frac{\partial \mathrm{u}}{\partial x}+\mathrm{v}\frac{\partial \mathrm{u}}{\partial y}\right)=-\frac{\partial P}{\partial x}+\frac{\partial}{\partial \mathrm{x}}\left(\mu_{eff}\frac{\partial u}{\partial \mathrm{x}}\right)+\frac{\partial}{\partial \mathrm{y}}\left(\mu_{eff}\frac{\partial u}{\partial y}\right) \quad (2)$$

$$\rho\left(u\frac{\partial \mathrm{v}}{\partial x}+\mathrm{v}\frac{\partial \mathrm{v}}{\partial y}\right)=-\frac{\partial P}{\partial y}+\frac{\partial}{\partial \mathrm{x}}\left(\mu_{eff}\frac{\partial v}{\partial \mathrm{x}}\right)+\frac{\partial}{\partial \mathrm{y}}\left(\mu_{eff}\frac{\partial v}{\partial y}\right)+\rho g\beta\left(T-T_{ref}\right) \quad (3)$$

Were

$$\mu_{eff}=\mu+\mu_t \quad (4)$$

μ_{eff} is the effective viscosity, which includes the dynamic viscosity (μ) and the turbulent viscosity μ_t provided by the (k e) turbulence model.

B is the thermal expansion coefficient.

g is the gravitational acceleration.

The conservation of thermal energy is expressed as:

Energy Conservation Equation

$$\mathbf{\rho C_p}\left(\mathbf{u}\frac{\partial \mathbf{T}}{\partial \mathbf{x}}+\mathbf{v}\frac{\partial \mathbf{T}}{\partial \mathbf{y}}\right)=\frac{\partial}{\partial \mathbf{x}}\left(\mathbf{k_{eff}}\frac{\partial \mathbf{T}}{\partial \mathbf{x}}\right)+\frac{\partial}{\partial \mathbf{y}}\left(\mathbf{k_{eff}}\frac{\partial \mathbf{T}}{\partial \mathbf{y}}\right) \quad (5)$$

$$k_{eff}=k+k_t \quad (6)$$

k_{eff} is the effective thermal conductivity.

k_t is the turbulent thermal conductivity, which is commonly modeled from μ_t using the following relation:

$$k_t=\frac{\mu_t c_p}{Pr_t} \quad (7)$$

Avec le nombre de Prandtl turbulent (souvent pris entre 0.85 et 1).

where Pr_t is the turbulent Prandtl number, commonly taken between 0.85 and 1.

Standard k–ε Turbulence Model

In the present study, the Rayleigh number (Ra) is significantly higher than the critical value of (10^9); therefore, the flow is considered turbulent [21]. Consequently, a mathematical model is required to describe the turbulent flow behavior of the fluid inside the system. The standard (kepsilon) turbulence model **i**s adopted in the present study [22].

Turbulent Kinetic Energy (k) Equation

$$u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+G_k-\varepsilon \quad (8)$$

Turbulent Dissipation Rate ε

$$u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}+\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right]+C_1G_k\frac{\varepsilon}{k}-C_2\frac{\varepsilon^2}{k}\right. \quad (9)$$

With:

G_k: generation of turbulence kinetic energy due to shear;

$\sigma_k, \sigma_\varepsilon, C_1, C_2\ et\ C_\mu$: empirical constants of the model.

Fluid Properties

Air was considered as an ideal gas under standard conditions, with a temperature of 300 K and a pressure of 1 atm. The thermophysical properties of the fluid are presented in Table 1.

Table 1: Thermophysical properties of air.

Fluide properties T=300K	ρ $\left[{}^{kg}/_{m^3}\right]$	C_p $\left[{}^{J}/_{kg.K}\right]$	μ $\left[{}^{kg}/_{m.s}\right]$	λ $\left[{}^{W}/_{m.K}\right]$	β $\left[{}^{1}/_{K}\right]$	Pr
air	1.117	1004	1.85×10^{-5}	0.0262	3.333×10^{-3}	0.707

The physical properties of the materials used for the components of the chimney solar [23]

Table 2. Physical properties of the materials used for the components of the chimney solar.

Physical properties	Glass	Absorber	Wall
Density $\left[{}^{kg}/_{m^3}\right]$	2500	2160	2719
Thermal conductivity $\left[{}^{W}/_{m.K}\right]$	1.15	1.83	202.4
Heat capacity $\left[{}^{J}/_{kg.K}\right]$	750	710	871
Transmissivity	0.9	opaque	opaque
Absorption coefficient	0.03	0.9	0
Refractive index	1.526	1	1
Emissivity	0.1	0.9	1
Thickness	0.004	0.5	0.00125

Evaluation of Solar Chimney Performance

The performance of a solar chimney is generally evaluated based on the ventilation flow rate V_{rate}, which is usually expressed in m³/s and is given by the following equation.

$$V_{rate} = \frac{m}{\rho_{air}} \quad (10)$$

with :

m: Airflow rate through the chimney.

ρ_{air}: The air density inside the chimney

Dans de nombreuses études, le nombre de renouvellements d'air par heure (ACH) est utilisé comme indicateur clé pour évaluer les performances des cheminées solaires. Il constitue une pour des locaux comme les salles de conférence, les cuisines, ou les espaces liés aux soins

Findings and Discussion

This section is devoted to the presentation and analysis of the results obtained from the numerical simulation carried out using ANSYS Fluent. The study focuses on the implementation of a natural ventilation system in a room, based on a passive device using a solar chimney to induce airflow.

The obtained results are examined in detail in the following sections. The analysis focuses mainly on the distributions of air velocity and temperature, as well as the flow patterns generated within the studied space. These parameters are used to evaluate the effectiveness of the passive solar ventilation system and to assess its thermal and aerodynamic performance.

Mesh Selection

The effect of the mesh on the numerical results was investigated to determine whether the obtained solution is mesh-independent. For this purpose, three mesh configurations were tested, containing 32,960, 36,562, and 41,584 element, respectively.

Figure 1 illustrates the variation in air temperature at the outlet of the solar chimney for each mesh configuration under the following conditions: ambient temperature: 300 K and incident solar radiation: 600 W/m².

The curves obtained for the three mesh configurations show almost perfect agreement, indicating that further mesh refinement has no significant effect on the results. This observation suggests that the solution can be considered mesh-independent within the investigated range.

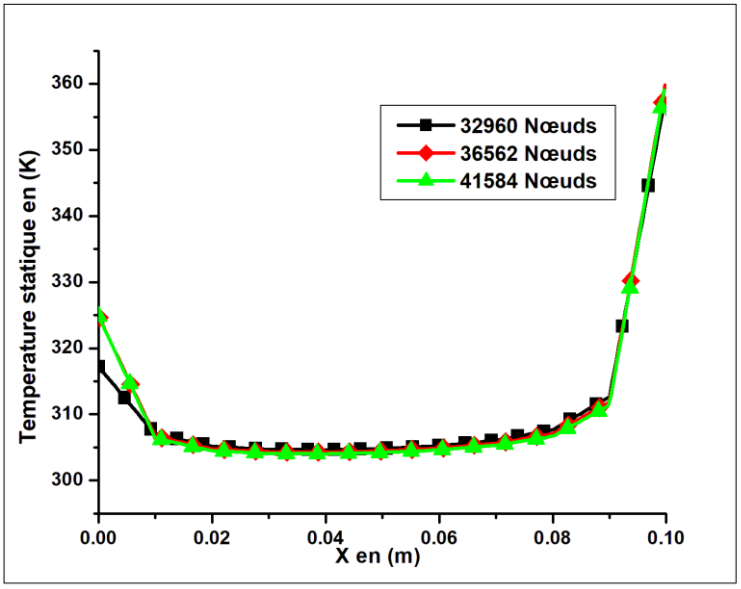


Figure 1. Variation in air temperature.

Table 3 presents the ventilation rate and airflow rate results for a room with a volume of 72 m³. It can be observed that these results become insensitive to the number of nodes. Therefore, the intermediate mesh was selected as an appropriate choice for the remainder of the study, as it provides a good compromise between numerical accuracy and computational cost.

Table 3. Mesh selection

Number of elements	32960	36562	41584
Airflow rate (m^3/h)	69.147	73.197	75.38
Ventilation rate ACH (h^{-1})	2.561	2.711	2.792

Validation of the Numerical Model by Comparison with Literature Data

Figure 2 compares the results of the present simulation, performed using the ANSYS Fluent code, with the theoretical and experimental data reported by Mathur et al. [24] for a room with a volume of 72 m³ and a chimney width of **0.1 m**. This comparison highlights the variation of the air change rate (ACH) as a function of solar irradiation.

The quantitative comparison between the numerical results obtained in the present study and the experimental data reported by Mathur et al. [24] shows satisfactory agreement under the considered operating conditions, thereby confirming **the** reliability and validity of the numerical model used in this study.

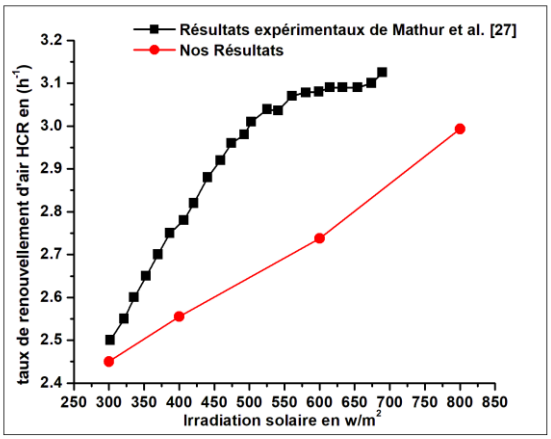


Figure 2. Effect of solar radiation intensity on the air change rate (ACH).

Effect of Solar Radiation Intensity on Natural Ventilation

To evaluate the effect of solar radiation intensity on the behavior of natural ventilation, numerical simulations were carried out for four solar irradiance levels: 400, 600, 800, and 1000 W/m². A room with a length of 3 m and a height of 3 m was considered in order to limit the number of mesh nodes and reduce the computational time. The following parameters were kept constant throughout the study: chimney width**:** b=0.1 m and ambient temperature: T = 300 K.

Figure 3 presents the velocity profiles at the chimney outlet as a function of solar irradiance. It can be observed that the different profiles exhibit a similar shape, with the highest velocities occurring near the chimney walls, particularly close to the absorber wall and, to a lesser extent, near the glazed wall. These regions correspond to areas where heat transfer is most significant, in accordance with the no-slip condition imposed at the boundaries. As the distance from the absorber and glass walls increases, the mean flow velocity decreases significantly.

Since the chimney outlet cross-sectional area remains constant, it can be inferred that most of the outgoing airflow is concentrated in the regions adjacent to the absorber wall and, to a lesser extent, near the glazed wall.

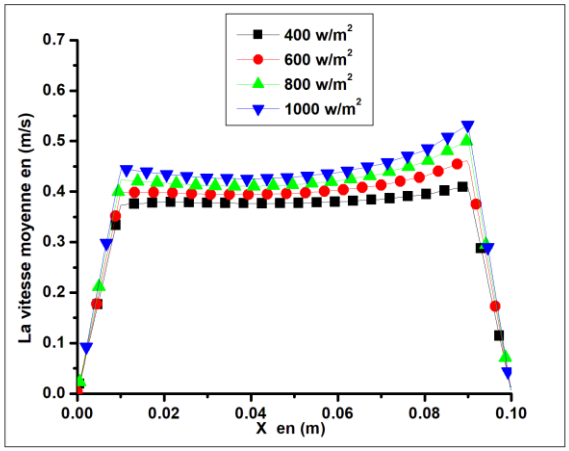


Figure 3. Velocity profiles at the chimney outlet as a function of solar irradiance.

Figure 4 presents the variation in the volumetric flow rate through the chimney as a function of solar irradiance. The increase in volumetric flow rate with increasing solar irradiance can be attributed to the local heating of the air near the absorber, which induces a buoyancy force that promotes upward natural convection. This process increases the volumetric flow rate of the airflow, thereby leading to a significant improvement in the air change rate.

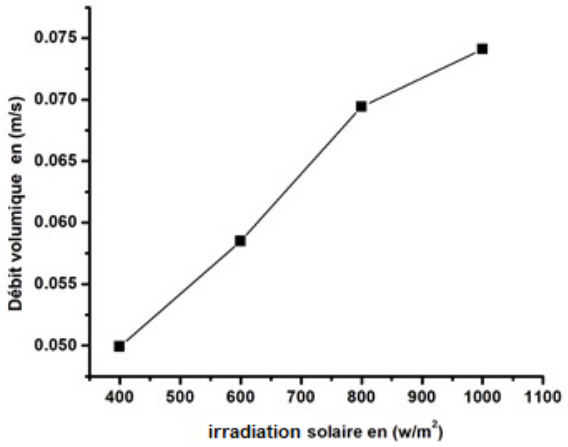


Figure 4. Effect of solar irradiance on the volumetric airflow rate (for b = 0.1 m).

Figure 5 illustrates the temperature profiles at the chimney inlet as a function of solar irradiance. It can be observed that these profiles exhibit a similar shape regardless of the solar irradiance level considered, with the maximum temperatures occurring near the absorber. More specifically, the temperature reaches a maximum peak near the absorber wall, while a second, slightly lower peak is observed near the glazed wall. These regions correspond to the areas where heat transfer is most intense, owing to the absorbed solar radiation and the thermal exchanges between the surfaces and the air.

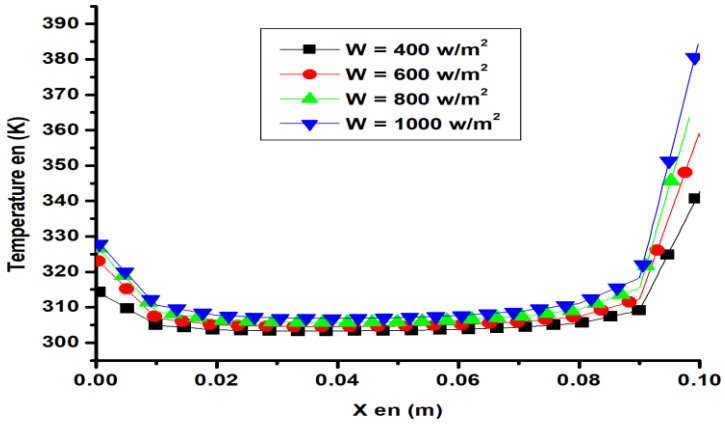


Figure 5. Variation of temperature along the width of the solar chimney outlet.

Effect of the Solar Chimney Width "b"

To evaluate the influence of the solar chimney width on natural ventilation, simulations were carried out for four different chimney widths: b = 0.10, 0.15, 0.20, and 0.25 m. The following conditions were kept constant throughout the study: a solar irradiance of 600 W/m² and an ambient temperature of T = 300 K.

Figure 6 presents the velocity profiles at the chimney inlet as a function of the solar chimney width. It can be observed that all the velocity profiles exhibit a similar shape, with the maximum velocities occurring mainly near the glazed wall and, to a lesser extent, near the absorber wall, where heat transfer is most significant.

It can be seen from the figure that the maximum velocities are located very close to the walls, while the velocity becomes zero at the wall surfaces due to the no-slip effect, in accordance with the boundary conditions imposed on the glass and absorber walls. Away from the walls, i.e., in the central region of the cross-section, the mean flow velocity remains relatively low.

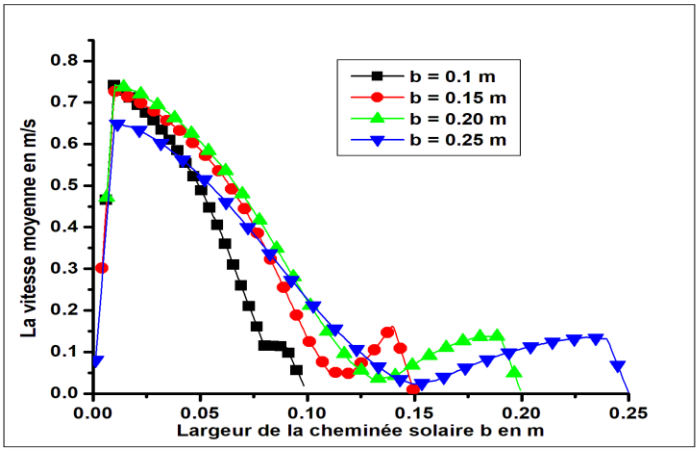


Figure 6. Velocity profiles at the chimney outlet as a function of its width.

Figure 7 presents the variation in the air mass flow rate at the chimney outlet for different solar chimney widths. It is observed that increasing the chimney width leads to a gradual increase in the mass flow rate up to an optimal width of b = 0.15 m. Beyond this value, the mass flow rate tends to stabilize.
This trend can be explained by the decrease in the kinetic energy of the flow resulting from the enlargement of the chimney cross-sectional area. Once the cross-sectional area exceeds a critical dimension, the gain resulting from the increased passage area is offset by the decrease in air velocity, thereby limiting the increase in the mass flow rate.
Therefore, it is essential to consider the geometrical dimensions of the solar chimney when designing natural ventilation systems, as they have a significant impact on the overall performance of the system.

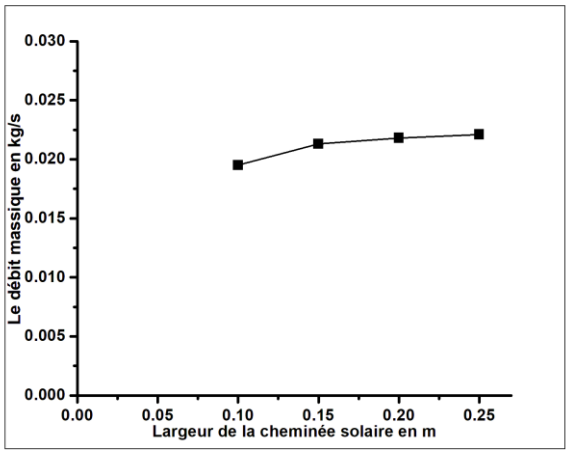


Figure 7. Effect of chimney width on the volumetric airflow rate at a solar irradiance of 600 W/m².

Figure 8 presents the temperature profiles at the chimney outlet as a function of the solar chimney width. The profiles exhibit a similar pattern, with the highest temperatures occurring near the absorber, and to a lesser extent near the glazed wall, where heat transfer is most significant. Furthermore, it can be observed that the air temperature near both the hot wall and the glazed wall decreases as the chimney width increases**.**

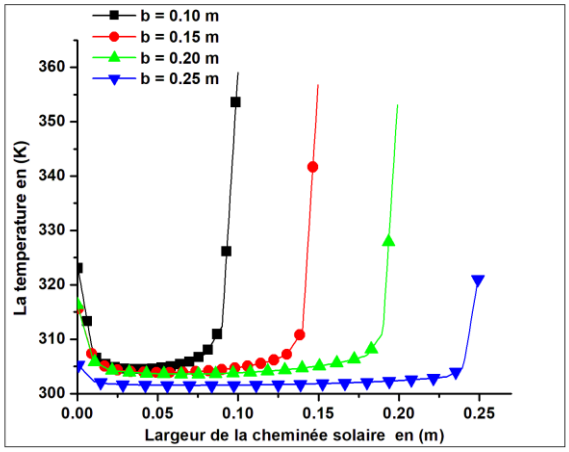


Figure 8. Profil de température en fonction de la largeur à la sortie de la cheminée.

Conclusion and Recommendations

Ventilation assisted by a solar chimney was investigated through a numerical simulation approach using the ANSYS Fluent software. The main objective was to evaluate the aerodynamic and thermal performance of such a system in order to propose a passive, energy-efficient solution adapted to the thermal comfort requirements of buildings.
The analysis of the results led to several important findings:

- Solar irradiance is the key performance factor of the solar chimney**.** Increasing solar irradiance leads to an increase in air temperature and, consequently, an increase in the airflow rate and air change rate (ACH). However, excessively high irradiance levels may adversely affect indoor thermal comfort.
- The chimney geometry, particularly its width, has a significant effect on flow velocities, mass flow rate, and temperature distribution. An optimal width of approximately 0.15 m was identified, beyond which the additional gains become marginal.

Overall, these results demonstrate that the solar chimney is an effective passive solution for improving natural ventilation in buildings while reducing dependence on mechanical air-conditioning systems. However, to ensure optimal thermal comfort, the system design must be adapted to the local climatic conditions and the specific characteristics of the building.

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QUORUM SENSING CONTROLS BIOFILM FORMATION IN MARINE ISOLATES

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This study aims to test marine microorganism for their biofilm forming capability using the crystal violet *in vitro* microplate assay. We examined that whether patulin and penicillic acid, two well-known quorum sensing inhibitors (QSI) for human pathogen *Pseudomonas aeruginosa* PAO1, can prevent biofilm formation. This study reports, for the first time, the successful amplification of a putative *luxS* gene homologue in the marine microorganism *H. pacifica* ATCC 27122, as well as a log 3 fold expression of AI-2 during early and mid-exponential growth in marine nutrient broth batch cultures. Degenerated primers were designed based on the *luxS* protein sequence of ten gram-negative, □-, □- and □-proteobacteria, and used for *luxS* gene amplification in *H. pacifica*. AI-2 assays were carried out using the well-established *Vibrio harveyi* BB170 AI-2 bioluminescence assay. Effect of penicillic acid on AI-2 induction of *H. pacifica* showed strong inhibitory effect at non-growth inhibitory concentrations compared to patulin having adverse effect at the highest concentration (25 μM) tested in our study. QSIs effect on biofilm forming capability of marine isolates was isolate specific. Detection of bioluminescence in the autoinducer bioassay and the presence of a putative *luxS* gene orthologue are biochemical and genetic evidence for the production of a signalling molecule(s) and provide a first step in characterizing *H. pacifica* quorum sensing. Our study emphasize that QSI compounds must be selected in the specific system in which they are to function and they cannot easily be transferred from one QS system to another.

Key Words: *H. pacifica*, AI-2 assay, Patulin, Penicillic acid, *LuxS* gene

INTEGRATED ASSESSMENT OF PHYSICOCHEMICAL AND BACTERIOLOGICAL GROUNDWATER QUALITY FOR DRINKING AND IRRIGATION IN THE FEIJA REGION, SOUTHEASTERN MOROCCO

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Abstract
This study aimed to evaluate the impact of phytosanitary products on the quality of surface and groundwater. The protocol was developed using a combined approach involving field analysis, water sampling, and surveys with farmers and retailers. The research was conducted in an intensive agricultural region located in the FEIJA area in southern Morocco. Water samples were collected and analyzed monthly throughout the study period at various locations, including rivers, agricultural wells, and irrigation canals. Laboratory analyses included the detection of pesticide residues (herbicides, fungicides, insecticides, and acaricides). And highlights the impacts of agricultural overexploitation and climate change. Using geospatial analysis (GIS), he assesses the suitability of water for domestic and agricultural uses through seasonal sample analyses. This article describes a reliable and effective analytical method for determining and detecting pesticides in eight wells from 2024 to 2025, in addition to the scientific analysis of these wells. The researchers used advanced statistical methods to determine the impact of pesticides on water quality in the Feija region. The results revealed the presence of phytosanitary products in the water, including fungicides, herbicides, acaricides, and insecticides. The analyses indicate a non-significant relationship between groundwater quality and the use of phytosanitary products in the FEIJA area in southeastern Morocco. The Feija aquifer has a heterogeneous composition, including Plio-Quaternary terrains of variable thickness. The analysis identifies various chemical facies of groundwater, including calcium bicarbonate, sodium chloride, and chloride sulfate, calcium, and magnesium. These characteristics reflect the influence of human activities and natural conditions on water quality
Keywords: Groundwater quality; Pesticide residues; Phytosanitary products; Agricultural pollution; Feija aquifer; GIS.

PLASTIC POLLUTION IN AQUATIC ECOSYSTEMS: EMERGING THREATS AND IMPLICATIONS

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Abstract

Plastic pollution has emerged as one of the most pervasive and persistent environmental threats to aquatic ecosystems worldwide. Its longevity, mobility, and toxicity make plastics, especially microplastics a critical challenge for biodiversity conservation, fisheries sustainability, and human health. The resilience of plastics in aquatic environments means they can travel long distances, fragment into smaller particles, and persist for decades, thereby disrupting ecosystem processes. This study provides a review of the sources, pathways, and ecological impacts of plastic pollution, focusing on inland and marine water systems. Land - based activities such as poor waste disposal, urban runoff, and industrial discharge, alongside ocean-based inputs from shipping, aquaculture, and fishing gear losses, are the dominant contributors to plastic accumulation. River networks act as major transport pathways, carrying mismanaged plastics from terrestrial environments into lagoons, estuaries, and the open ocean. The ecological consequences are severe: microplastics are ingested by fish, invertebrates, and plankton, resulting in physical injury, gut blockage, and exposure to harmful additives and adsorbed pollutants. These contaminants bioaccumulate within food webs and bio magnify across trophic levels, ultimately posing risks to human consumers who depend heavily on aquatic protein sources. Furthermore, plastic debris alters habitats by smothering benthic ecosystems, reducing water quality, and facilitating the spread of invasive species. Addressing this growing challenge requires integrated, multi-level solutions. Effective waste management systems, circular economy strategies, and innovative biodegradable materials can reduce plastic inputs at the source. At the same time, public education campaigns and policy enforcement are essential to promote behavioral change and compliance with anti-pollution regulations. Regional and global collaborations are also necessary to harmonize monitoring standards and strengthen transboundary governance of marine litter. In conclusion, mitigating plastic pollution in aquatic environments demands a holistic and collaborative approach that combines technological innovation, strong institutions, and public participation. Without urgent action, plastic pollution will continue to undermine aquatic ecosystem health, fisheries productivity, and human well-being.

Keywords: aquatic ecosystems, environmental health, fisheries, microplastics, sustainability, waste management

1.0 Introduction

The global production of plastics has increased exponentially over the past decades, with estimates exceeding 350 million metric tons annually (Pilapitiya & Ratnayake, 2024). This unprecedented growth reflects plastics' versatility, affordability, and wide application across industries, but it also underpins a mounting environmental crisis. Due to their durability and resistance to natural degradation, plastics accumulate in terrestrial and aquatic ecosystems, creating ecological, economic, and human health risks (Kumar *et al*., 2021). Unlike organic matter, plastics persist for centuries, during which they undergo physical, chemical, and biological transformations that exacerbate their environmental footprint.

Aquatic ecosystems like rivers, lakes, estuaries, and oceans are particularly vulnerable to plastic contamination. Water currents facilitate the wide dispersal of plastic waste, enabling it to travel long distances from its source. Over time, larger plastic debris fragments into microplastics (<5 mm) and even nanoplastics, which are more readily ingested by aquatic organisms and more difficult to remove from the environment. These smaller particles are of growing concern because they not only threaten aquatic biodiversity but also act as vectors for persistent organic pollutants (POPs), heavy metals, and pathogenic microorganisms (Sunny *et al*., 2025).

In Nigeria, the challenge is amplified by rapid urbanization, weak waste management infrastructure, and high plastic consumption. Studies have reported that a significant proportion of mismanaged plastic waste in urban centers finds its way into nearby rivers and lagoons, where it disrupts ecological balance and undermines fisheries productivity (Ekanem *et al*., 2024). Plastic debris (Figure 1) affects aquatic organisms through entanglement, ingestion, and habitat alteration, while humans are increasingly

exposed to microplastics via seafood consumption and contaminated drinking water (Alberghini *et al*., 2022). These impacts pose long-term risks to food security, public health, and sustainable development.

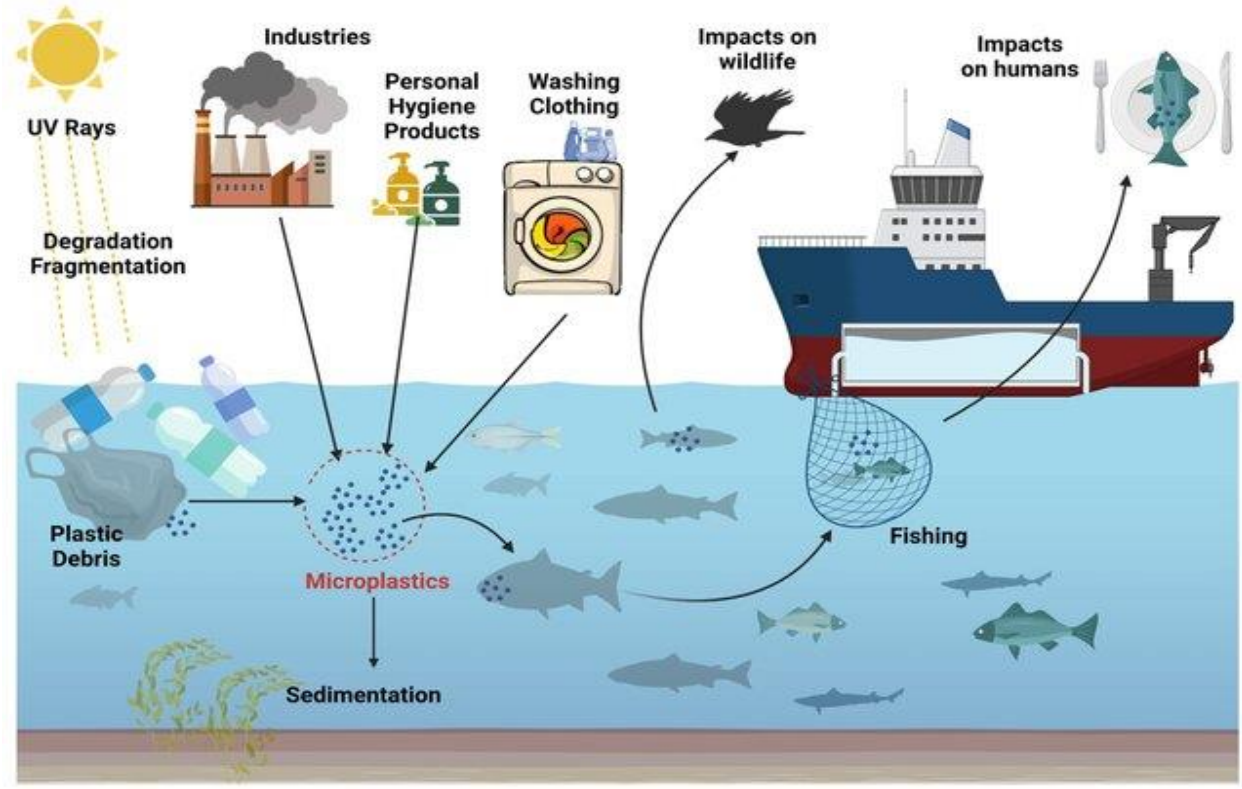


Figure 1: Microplastics in Aquatic environment

Source: Ziani *et al*., 2023

Understanding the pathways, transformations, and impacts of plastic pollution is therefore critical for designing effective interventions. Such knowledge informs policies on waste reduction, circular economy strategies, and regulatory frameworks aimed at mitigating the ecological footprint of plastics. Furthermore, it provides scientific evidence to strengthen regional and global collaborations targeting marine litter, while ensuring that solutions are context-specific and inclusive. Addressing plastic pollution in aquatic ecosystems is not only an environmental necessity but also a socio-economic imperative for safeguarding biodiversity, fisheries, and human well-being.

2.0 Methodology

2.1 Data Source

This study employs a narrative review approach to consolidate and critically analyze contemporary knowledge on plastic pollution in aquatic ecosystems, with a particular emphasis on the Nigerian context. The review synthesizes evidence from peer-reviewed journal articles, institutional reports, and global databases published between 2020 and 2025, ensuring that the discussion is grounded in the most recent advances in the field.

2.2 Search Strategy

A systematic search strategy was adopted using academic databases such as Google Scholar, ScienceDirect, and ResearchGate. Search queries combined primary keywords, plastic *pollution*, *microplastics*, *aquatic ecosystems*, *marine debris*, and *Nigeria* with Boolean operators to maximize retrieval of relevant literature. Grey literature, including policy briefs and technical reports from global environmental agencies, was also consulted to capture practice-oriented insights and regional perspectives.

2.3 Eligibility and Selection Criteria

Studies were excluded if they lacked empirical evidence, were not peer-reviewed, or did not explicitly address plastic pollution in aquatic environments.

Following selection, data were analyzed thematically using a four-domain framework; sources of plastic, pathways of plastics into aquatic ecosystems, ecological impacts and mitigation strategies.

2.4 Data Analysis

This methodological approach enables a holistic synthesis of current evidence, highlighting not only the environmental dimensions of plastic pollution but also the socio-economic trade-offs and policy imperatives for sustainable management. The narrative review further emphasizes context - relevant insights for Nigeria, while situating the findings within broader global discourses on marine debris and microplastic contamination.

3.0 Results

3.1 Sources and Pathways of Plastic Pollution in the Aquatic Environment

Plastic pollution originates from multiple sources Figure 1), with both land-based and ocean-based activities contributing substantially to the problem.

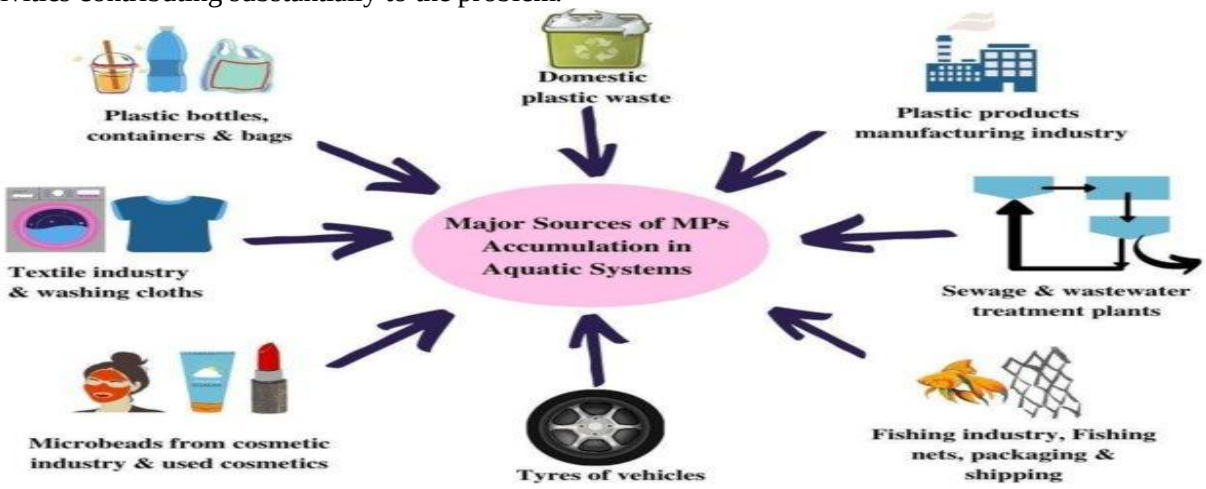


Figure 1: Major Sources of microplastics in Auqatic system.

Source: Katare *et al*., 2021

Table 1 provides a concise overview of the major sources and types of contaminants associated with aquatic environments. It highlights specific examples of these contaminants, their pathways of entry into aquatic systems, and the potential routes through which they may affect aquatic ecosystems. Understanding these sources and pathways is essential for identifying pollution hotspots and developing effective monitoring and management strategies. The table also provides relevant references to support the information presented.

Table 1. Sources and Pathways of Plastic Pollution in Aquatic Environments

Source	Examples	Pathways
Land-based sources	Household waste, packaging materials, industrial plastics, stormwater runoff	River discharge, wind transport, sewage effluent
Ocean-based sources	Discarded fishing gear, shipping waste, offshore platforms	Direct dumping, gear loss during fishing
Degradation products	Microplastics & nanoplastics from breakdown of larger plastics	Photodegradation, mechanical abrasion, chemical weathering
Waste mismanagement	Open dumping, poor recycling, uncontrolled landfills	Direct entry into waterways, leaching from dumpsites
Industrial activities	Plastic pellets (nurdles), microbeads from cosmetics, textile microfibers	Accidental spillage, wastewater discharge, atmospheric fallout
Agricultural sources	Mulch films, greenhouse plastics, irrigation pipes, pesticide containers	Runoff from farms, soil erosion, leaching

Source	Examples	Pathways
Aquaculture inputs	Plastic nets, feed bags, cages, floats	Wear and tear of equipment, accidental loss
Tourism & recreation	Plastic bottles, single-use cutlery, packaging, balloons	Littering along beaches, riverbanks, and boating areas
Atmospheric transport	Microplastics from tire wear, synthetic fibers, industrial dust	Deposition via wind and rainfall into rivers and oceans
Disaster-related inputs	Plastics from floods, hurricanes, tsunamis, and extreme weather events	Sudden discharge of debris into rivers, lakes, oceans

2.1 Ecological Impacts of Plastic Pollution

Table 2 summarizes the range of ecological impacts of plastic pollution across different aquatic organism groups, highlighting both the mechanisms and evidence from recent studies. Fish are highly vulnerable because they ingest microplastics, mistaking them for prey. **Marine mammals** are mostly impacted by entanglement in discarded fishing gear and ingestion of macroplastics. The s**eabirds**, such as *Fulmarus glacialis*, ingest floating plastics, which occupy stomach volume, reducing nutrient absorption and contributing to chick mortality and overall poor body condition. **Crustaceans** ingest microplastics that impair their molting cycles and reduce energy reserves while b**ivalves** (mussels and oysters) act as filter feeders, making them particularly susceptible to microplastic accumulation. Zooplankton, being at the base of the food web, ingest microplastics which are then transferred tropically to higher-level organisms.

Table 2: Effects of Plastic Pollution on Aquatic Organisms

Organism Group	Type of Impact	Mechanism	Examples
Fish	Ingestion of microplastics; reduced growth; reproductive impairment	Plastics mistaken for food cause gut blockage; toxic chemical leaching disrupts endocrine systems	Reduced feeding efficiency in *Oreochromis niloticus*; histopathological damage in liver tissues
Marine mammals	Entanglement; ingestion of macroplastics	Plastic debris wraps around fins and neck; ingestion leads to internal injuries and starvation	Entanglement in fishing gear causing drowning in dolphins and seals
Seabirds	Ingestion of floating plastics; chick mortality	Plastics fill stomach cavity, reducing nutrient absorption	Declines in body condition in *Fulmarus glacialis* populations
Crustaceans	Microplastic ingestion; impaired molting	Ingestion leads to reduced energy reserves and slower molting cycles	Laboratory studies showing delayed growth in crabs exposed to polyethylene particles
Bivalves (mussels, oysters)	Microplastic accumulation; reduced filtration rates	Plastics clog gills and digestive tract; lower feeding efficiency	Accumulation of polypropylene and polystyrene in *Mytilus edulis*
Zooplankton	Ingestion; trophic transfer to higher levels	Microplastics ingested are passed to fish and other predators	Detection of microplastics in copepods leading to reduced reproduction rates

3.3 Mitigation Strategies for Plastic Pollution in Aquatic Ecosystems

Plastic pollution poses multidimensional challenges to aquatic ecosystems, fisheries, and human health. Consequently, mitigating its impacts requires a holistic, multi-level strategy that integrates technological innovations, governance frameworks, and community-based interventions.

a) **Technological Innovations**: Advancements in technology provide effective tools for preventing, reducing, and monitoring plastic pollution.

- ❖ Biodegradable and bio-based plastics: The development of plastics from renewable sources such as starch, algae, and polylactic acid offers an alternative to petroleum-based plastics. These materials degrade more quickly and minimize long-term persistence in aquatic systems (Ahsan *et al*., 2023).
- ❖ Advanced waste management systems: Innovations in waste sorting, recycling, and upcycling technologies improve recovery of plastics before they reach aquatic environments. Mechanical and chemical recycling are being increasingly applied to convert plastic waste into raw materials or fuels (Alaghemandi, 2024).
- ❖ Plastic capture and cleanup devices: River booms, ocean cleanup systems, and nanofiber filtration membranes are designed to intercept floating debris and microplastics before they disperse into oceans and lakes (Helinski *et al*., 2021).
- ❖ Smart monitoring technologies: Remote sensing, drones, and artificial intelligence (AI) are increasingly used for detecting and mapping plastic debris, enabling better decision-making for targeted interventions (Olawade *et al*., 2024).

b) **Governance Frameworks**: Effective governance underpins sustainable management of plastic pollution.

- ❖ International agreements and conventions: Global initiatives such as the UNEA resolution on plastic pollution (2022) and the MARPOL Convention regulate plastic waste from land-based and marine sources. These agreements foster transboundary cooperation and accountability.
- ❖ National legislation and policies: Many countries have enacted bans on single-use plastics (India, Indonesia), introduced extended producer responsibility (EPR) schemes (Japan, South Korea), and promoted circular economy frameworks (France, Belgium) to reduce plastic leakage (UNDP, 2024).
- ❖ Economic instruments: Plastic taxes, deposit-refund systems, and subsidies for recycling industries incentivize reduction in plastic production and encourage sustainable practices.
- ❖ Institutional strengthening: Enhancing the capacity of regulatory bodies ensures compliance with anti-pollution regulations and promotes sustainable fisheries management in plastic-impacted ecosystems.

c) **Community-Based Interventions**: Local participation is crucial for addressing plastic pollution, particularly in low- and middle-income countries where institutional capacity may be limited.

- ❖ Awareness and education campaigns: Public sensitization on the impacts of plastic pollution fosters behavioral change, such as reducing single-use plastics and improving waste segregation at source (Bano *et al*., 2024).
- ❖ Community clean-up programs: Initiatives like “beach cleans” and “adopt-a-river” schemes empower communities to take ownership of their aquatic environments. These efforts not only remove plastics but also strengthen stewardship.
- ❖ Informal waste sector engagement: In many developing regions, informal waste pickers play a significant role in recovering plastic waste. Supporting this sector with training, protective gear, and financial incentives enhances recycling rates while reducing poverty.
- ❖ Local innovations: Grassroots solutions, such as converting plastic waste into construction materials (bricks, tiles, road surfacing), provide livelihood opportunities while reducing environmental burdens (Mihai *et al.*, 2022).

Mitigation of plastic pollution in aquatic ecosystems requires a synergistic approach where technological innovations are supported by strong governance and reinforced by community participation. While emerging technologies offer pathways for waste reduction and monitoring, their success depends on robust policies and active societal engagement. Integrating these strategies within a circular economy framework can reduce plastic inputs, protect aquatic biodiversity, and safeguard fisheries and human health.

4.0 Discussion

The results highlight the multi-source and multi-pathway nature of plastic pollution in aquatic ecosystems. Plastics originate from a wide spectrum of human activities, both land-based and ocean-based, and are further amplified by secondary sources such as degradation products and disaster-related discharges. Plastics cause physical harm through entanglement and ingestion, leading to injury, reduced feeding efficiency, and death in aquatic species (Islam, 2025). Microplastics are particularly concerning because they are mistaken for food by fish, crustaceans, and zooplankton, leading to gut blockage and reduced growth rates (Ghosh *et al*., 2023). Toxic chemicals including bisphenol A (BPA), phthalates,

and persistent organic pollutants (POPs) can leach from plastics, bioaccumulate in tissues, and biomagnify through the food chain (Weis & Alava, 2023). This can impair reproduction, disrupt endocrine function, and increase mortality rates in aquatic species. Microplastics have been detected in seafood, table salt, and even drinking water (Chen et al., 2020). Ingestion by humans may cause inflammatory responses, oxidative stress, and potential toxic effects, although the full health implications are still under investigation (WHO, 2023).

Land-based inputs such as mismanaged household waste, stormwater runoff, and industrial discharge remain the dominant contributors in most regions, including Nigeria, due to inadequate waste collection and open dumping practices (UNEP, 2023, Ekanem et al., 2024). River networks serve as the main transport pathways, delivering mismanaged plastics into estuaries and coastal systems. Ocean-based sources, notably abandoned fishing gear and shipping waste, add to the problem, particularly in regions with intense maritime activity (FAO, 2022).

Emerging pathways, such as atmospheric transport of microplastics from tire wear and synthetic fibers, highlight the global reach of plastic pollution, showing that even remote aquatic systems are not immune (Kumar *et al*., 2021). Similarly, extreme weather events such as floods, hurricanes, and tsunamis can discharge large quantities of plastic debris in short periods, overwhelming local waste management systems (Kehinde et al., 2020). The results emphasize that plastic pollution is not just a gradual accumulation problem, but also one that can be exacerbated by climate-related disasters.

The ecological consequences spread across multiple trophic levels, showing that no group of aquatic organisms is spared. Fish, crustaceans, and bivalves are particularly vulnerable to microplastic ingestion, leading to gut blockage, reduced feeding efficiency, impaired growth, and tissue damage (Ahmad et al., 2025). These effects compromise fisheries productivity and aquaculture sustainability, with potential economic repercussions. Higher organisms, including marine mammals and seabirds, suffer entanglement and ingestion of macroplastics, often leading to injury, starvation, and mortality (NOAA, 2023). Zooplankton ingestion of microplastics is particularly concerning, as it facilitates trophic transfer, enabling plastics and associated toxins to move up the food web and ultimately reach human consumers (FAO, 2022).

The results therefore underscore the dual ecological and human health risks of plastic pollution. Bioaccumulation of plastics and associated chemicals across trophic levels threatens seafood safety, which is particularly critical for populations in developing countries such as Nigeria where fish remains a primary source of protein (Kehinde *et al*., 2020; Ekanem *et al*., 2024).

Addressing these results requires integrated mitigation strategies, as summarized in the review. Technological innovations such as biodegradable plastics, improved recycling technologies, and AI-driven monitoring offer promise for reducing inputs and improving management. However, without strong governance frameworks including enforcement of international conventions, bans on single-use plastics, and economic incentives the benefits of technology may be undermined (Ahsan *et al*., 2023; Olawade *et al*., 2024). Importantly, the results also show that community-based interventions remain central. Given that land-based sources dominate, engaging local communities in waste segregation, cleanup campaigns, and grassroots innovations (e.g., plastic-to-bricks initiatives) provides immediate and context-specific benefits, especially in low- and middle-income countries.

Taken together, the results point to plastic pollution as a complex, multi-scalar challenge requiring interventions at global, national, and community levels. Land-based inputs must be urgently reduced through improved waste management, while ocean-based losses, particularly abandoned fishing gear, require better regulation and accountability. Mitigation strategies must also be adaptive to climate variability, recognizing that extreme weather events can accelerate plastic influx into aquatic systems. Ultimately, integrating technology, governance, and community action within a circular economy framework provides the most robust pathway for safeguarding aquatic biodiversity, fisheries productivity, and human health (Bano *et al*., 2024; UNDP, 2024).

The interplay between these sources and pathways highlights that plastic pollution is not a single-point problem but a multi-source, transboundary issue. For instance, plastics entering rivers in Nigeria can eventually be transported to the Atlantic Ocean, where they accumulate in transoceanic gyres. Moreover, the fragmentation of plastics into micro- and nanoplastics increases their ecological persistence, as smaller particles are less detectable, more mobile, and more bioavailable to aquatic organisms.

Understanding these pathways provides the foundation for targeted interventions such as improving solid waste management systems at the local level, strengthening international regulations for shipping and fisheries, and advancing research into biodegradable alternatives to conventional plastics.

5.0 Conclusion

Plastic pollution in aquatic environments is a complex global challenge that requires coordinated action at local, national, and international levels. Reducing plastic leakage into water systems will require integrated waste management systems, public engagement, strict enforcement of environmental policies, and innovation in sustainable materials. Addressing this issue is essential to protect aquatic biodiversity, sustain fisheries, and safeguard human health.

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ADVANCING FOOD SAFETY IN ARTIFICIAL INTELLIGENCE: CURRENT PROGRESS, CHALLENGES, AND FUTURE DIRECTIONS

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Abstract

Food safety deserves the application of higher-level technology to shield customers from dietary illnesses and protect business reputations. The article focuses on artificial intelligence's current situation in the area of food sector, emphasizing the difficulties related to sharing data, encouraging interdisciplinary collaboration, providing training in data science and developing software for professionals in the field, and exploring the various uses of AI within the field of food safety. Machine learning models are discussed, which include a decision tree model that identifies vegetable diseases early on, improving crop superiority and security. The outcomes demonstrate the high rate of precision of the decision tree model. Using a parallel support vector machine model, researchers looked into a risk assessment model for dairy production. Numerous data sources, including analyses of dairy product data and amounts of pertinent components (like protein and sodium), are used to support the study. The accuracy of the algorithms was remarkably high. Moreover, deep learning models are discussed in which researchers looked at using them to handle hyperspectral data to predict shrimp freshness using both visible and near-infrared wavelengths. Based on the acquired deep structures, logistic regression, and a sparse autoencoder model were used to categorize the freshness of the shrimp. The utilization of machine learning as well as deep learning aids to identify patterns in food safety. The suggested algorithms present multiple goals for maximizing the layout and employ a meta-heuristic and the deep neural network method for optimizing the food safety assessment.

Keywords: Food safety, decision tree, sparse autoencoder, Bayesian network, decision tree.

AN EVALUATION STUDY OF THE SURVIVAL RATE OF PLANTS ON RECLAMATED LAND IN A FORMER COAL MINE AREA

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ABSTRACT
Reclamation is a critical component of sustainable post-mining land management, aiming to restore degraded lands so they can function ecologically and economically. One of the most important indicators of reclamation success is the plant survival rate. This study aimed to evaluate the effectiveness of reclamation at PT. Komunitas Bangun Bersama (PT. KBB), focusing on the survival percentage of reforestation species. The research employed a quantitative approach with stratified random sampling applied to 8 (eight) plots.The selected tree species included Sengon (*Albizia chinensis*), Sengon Buto (*Enterolobium cyclocarpum*), Mahogany (*Swietenia mahagoni*), Trembesi (*Samanea saman*), Johar (*Cassia siamea*), and Gliricidia (*Gliricidia sepium*). The survival, mortality, and stressed condition rates of each plant were recorded and analyzed. Results indicated a survival rate of 81.33% in PIT Arjuna (categorized as “moderate”) and 62% in PIT Kresna (categorized as “good”). Several environmental and managerial factors contributed to these outcomes, including soil fertility, pH levels, planting time, species selection, and post-planting care. The study concluded that PT. KBB’s reclamation program met national reclamation success standards, yet improvements are needed, especially in soil management and species-site matching. These findings can serve as a reference for the continuous development of effective and sustainable reclamation strategies.
Keywords: Reclamation, revegetation, survival rate, post-mining land, plant success.

BLOCKING ANTIBIOTIC POLLUTION AND BACTERIA CONTAMINATION VIA EFFICIENT PHOTOCATALYSIS USING N-CARBON DOTS DOPED NI@TIO2

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Abstract
Wastewater contamination from pharmaceuticals and pathogens poses an urgent global challenge that conventional water treatment processes struggle to address effectively. This research reports the multifunctionalities of Ni-doped titania (Ni@TiO_2) decorated with green nitrogen-doped carbon quantum dots (NCD), as a visible-light photocatalyst for drug degradation and as an antibacterial agent. To overcome the limitations of titania-based catalysts, a dual-modification strategy is proposed. The dual presence of NCD and Ni introduces localized energy levels that successfully narrow the TiO_2 bandgap, promoting charge carrier separation and photo-electron transfer and optimizing photocatalytic behaviour. Besides, the NCDs act as electron sinks and photo-induced electron transfer mediators, promoting charge separation and transfer at the heterojunction interface and extending charge-carrier lifetime. The presence of NCD and the Ni addition Ni@TiO_2/NCD (NCD=4% wt) composite achieved high paracetamol degradation (≈99%, TOC removal of 98%), ceftriaxone (70%), and vancomycin (75%) after 180 minutes of irradiation. Antibacterial activity was shown by Ni@TiO_2/NCD (NCD=4% wt), reducing the viability of S. aureus by 96.71% and 68.37%, and E. coli by 95.41% and 68.23%, at 1000 and 500 µg/mL, respectively. Finally, MIC values and residual antibacterial activity of water containing photocatalytically treated antibiotics prove the great performance of the developed composite system in achieving multiple functions, emphasizing its potential in wastewater treatment and infection control.
Keywords: Photocatalysis; Carbon quantum dots; Antibacterial activity; Water decontamination; Catalysts.

MICROBIOLOGICAL STUDY OF SOME HONEYS FROM THE CONSTANTINE REGION

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Abstract
Honey possesses well-known natural antimicrobial properties due to its high osmotic pressure, acidic pH, and hydrogen peroxide production. Nevertheless, it is not a sterile product and may harbor resistant microorganisms, including osmophilic yeasts and spore-forming bacteria such as *Bacillus* and *Clostridium*. Their presence can impair honey quality, shorten its shelf life, and pose potential health risks, particularly for immunocompromised individuals and infants. This study aims to assess the microbiological quality of commercial honeys marketed in the Constantine region (Algeria) and to determine the origin of their contamination, whether from the hive environment or from post-harvest handling practices.
The investigation analyzed 16 commercial honey samples from Constantine and 7 control samples taken directly from hive frames and the extractor to trace contamination origin. Microbiological analyses included the enumeration of Total Aerobic Mesophilic Flora (FAMT) on PCA medium using the pour-plate method incubated at 30°C for 72 hours, the enumeration of yeasts and molds on OGA medium by surface spreading incubated at 25°C for 72 hours, and the detection of sulfite-reducing *Clostridium* on VF medium after heat shock at 80°C for 10 minutes to select spores, followed by anaerobic incubation at 37°C for 48 hours.
Results showed that 5 commercial samples (31.25%) exceeded the recommended FAMT limits, with counts ranging from 1.85×10^3 to 17.15×10^3 CFU/g. Microscopic examination revealed the presence of *Bacillus* spp. and coagulase-negative *Staphylococcus* spp. No *Clostridium* were detected, and yeast/mold counts remained below 30 CFU/g, complying with ISO 21527-1 standards ($<10^2$ CFU/g). Critically, all control samples (hive frames and extractor) remained negative or showed negligible contamination.
The comparison clearly demonstrates that bacterial contamination originates from post-harvest handling practices such as manipulation, filtration, and packaging rather than from the hive environment. This study underscores the urgent need for improved hygiene training for beekeepers in Constantine and the implementation of routine microbiological controls to ensure the production of safe, high-quality honey for consumers.
Keywords: Honey, microbiological quality, Total Aerobic Mesophilic Flora (FAMT), yeasts and molds, Clostridium, Constantine.

NATURAL ANTIOXIDANTS AND ANTIMICROBIALS IN FUNCTIONAL FOODS: CURRENT ADVANCES AND FUTURE PERSPECTIVES

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Abstract
The growing demand for healthier, safer, and more sustainable food products has increased interest in natural antioxidants and antimicrobial agents as promising alternatives to synthetic additives. Functional foods, in particular, provide an important platform for incorporating bioactive compounds with antioxidant and antimicrobial properties while potentially enhancing nutritional and health benefits. This review provides a comprehensive overview of recent advances in the application of naturally derived antioxidants and antimicrobials in functional foods, with particular emphasis on their major sources, mechanisms of action, technological applications, and current challenges. Plant-derived compounds, including phenolic acids, flavonoids, tannins, essential oils, carotenoids, and other phytochemicals, as well as bioactive compounds from microbial and animal sources, are discussed in relation to their ability to inhibit oxidative deterioration and suppress foodborne microorganisms. Recent approaches such as encapsulation, nanoemulsions, edible coatings, active packaging, and combination strategies are highlighted as promising technologies for improving the stability, bioavailability, and controlled release of these compounds in food systems. Particular attention is given to the interactions between natural bioactive compounds and food matrices, which can significantly influence their efficacy, sensory properties, and technological performance. Despite their considerable potential, limitations related to stability, bioavailability, sensory impact, standardization, regulatory requirements, and large-scale application remain important barriers to commercialization. Future research should therefore focus on innovative delivery systems, synergistic combinations, sustainable extraction methods, and evidence-based evaluation of safety and efficacy. Overall, natural antioxidants and antimicrobials represent promising tools for the development of next-generation functional foods with improved stability, safety, quality, and potential health-promoting properties.
Keywords: Natural antioxidants; Natural antimicrobials; Functional foods; Bioactive compounds; Food preservation; Food safety.

EFFICACY OF KAOLIN IN CONTROLLING SITOPHILUS ZEAMAIS

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Abstract
Sitophilus zeamais is one of the most important pests of stored products in Iran and the world, and chemical control is the most common control method. The aim of this research is to evaluate the effect of kaolin as safer methods compared to common chemical pesticides in controlling the population of different stages of *S. zeamais*. In this regard, a study was conducted in a grain storage with an area of 2000 thousand square meters located in the urmia area of urmia city in the form of a completely randomized basic design with four treatments. The treatments studied in this research were control, with kaolin at a ratio of 1, 2, 3 and 4%. The results obtained from this research showed that the use of kaolin 4% had a more significant and effective control on the population of ***S. zeamais*** compared to another concentration of kaolin. According to the obtained results, the efficiency of kaolin (4%), kaolin (3%) and kaolin (2%) in controlling *S. zeamias* was 79.15, 72.38, and 69.18%, respectively. Kaolin (1%) treatment was equal to Kaoli2 (2%). In general, based on the results obtained from the present research, the consumption of low-risk and biocompatible compounds such as kaolin in control the population of *S. zeamais* and reduce the damage of this pest.
Keywords: *Sitophilus zeamais*, insecticide, kaolin

SENSORY EVALUATION AND PERCEPTION OF MILK QUALITY BY ALGERIAN CONSUMERS

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Abstract
Milk is a food of major nutritional and economic importance, whose quality is assessed not only through its physicochemical and microbiological characteristics but also through its sensory properties. The present study aimed to analyze the relationship between the sensory evaluation of milk and consumers' perception of its quality. More specifically, it sought to identify the sensory attributes that most influence product appreciation and to compare consumer perceptions of industrial UHT milk (Candia®) and natural milk. The study was conducted with a panel of 30 untrained participants. Consumers evaluated several sensory attributes of both types of milk using a 9-point hedonic scale. The criteria assessed included color, odor, taste, texture, creaminess, and overall acceptability. The collected data made it possible to assess consumer preferences and identify the factors influencing their perception of quality. The results showed that natural milk generally received moderate scores for taste, texture, and overall acceptability. In contrast, industrial Candia® milk was perceived as more homogeneous and stable in terms of sensory quality, particularly regarding color and certain attributes related to preservation. The findings also revealed variability in individual responses, reflecting the influence of personal preferences, consumption habits, and consumer expectations. In conclusion, this study confirms that sensory characteristics are major determinants of the perceived quality of milk. Taste and texture emerged as the most influential factors affecting product acceptability. These findings highlight the importance of sensory evaluation in the development and improvement of dairy products in order to better meet consumer expectations and enhance product acceptance in the marketplace.
Keywords: milk, sensory evaluation, perceived quality, consumers.

NUMERICAL OPTIMIZATION OF COUPLING MATRICES FOR PSEUDO-ELLIPTIC MICROWAVE FILTER SYNTHESIS

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Abstract
This work presents a numerical approach for the synthesis of pseudo-elliptic microwave filters using coupling matrix optimization. Conventional synthesis methods, such as Levy's approximation and table-based techniques, may have limited accuracy and flexibility, particularly when transmission zeros are located close to the passband.
The proposed method formulates filter synthesis as an optimization problem in which the coupling coefficients and external quality factors are adjusted to minimize the difference between the calculated and desired scattering responses. A frequency-weighted objective function is used to improve the control of the transmission and reflection characteristics.
The method is applied to an eighth-order pseudo-elliptic bandpass filter with finite transmission zeros at different normalized frequencies. The obtained results show good agreement with the desired response and demonstrate the ability of the proposed approach to maintain high selectivity for different transmission-zero locations.
Keywords: Coupling matrix optimization, pseudo-elliptic filters, transmission zeros, microwave filter synthesis, numerical optimization.

ENGINEERING SECURE AND SCALABLE BLOCKCHAIN-ENABLED PAYMENT SYSTEMS: SECURITY, CONSENSUS OPTIMIZATION, AND ECONOMIC ADOPTION CHALLENGES

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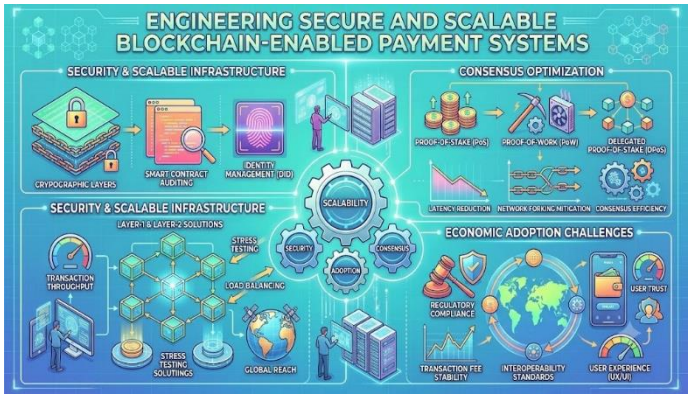
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Abstract
Blockchain technology has emerged as a transformative paradigm for modern digital payment infrastructures by providing decentralized trust, cryptographic security, immutable transaction records, and programmable financial services. However, engineering blockchain-enabled payment systems capable of supporting global-scale financial transactions remains constrained by persistent challenges associated with cybersecurity, consensus efficiency, network scalability, interoperability, and user adoption. This study examines contemporary approaches for engineering secure and scalable blockchain-enabled payment systems, with particular emphasis on security mechanisms, consensus optimization strategies, and the economic barriers influencing widespread adoption. The research employed a systematic literature review (SLR) methodology following the PRISMA 2020 framework to synthesize evidence from peer-reviewed publications indexed in IEEE Xplore, ACM Digital Library, SpringerLink, ScienceDirect, MDPI, and Google Scholar between 2020 and 2026. Findings indicate that hybrid consensus mechanisms, Proof-of-Stake (PoS), Byzantine Fault Tolerant (BFT) protocols, sharding, Layer-2 architectures, and zero-knowledge cryptographic techniques significantly improve transaction throughput while reducing computational overhead and energy consumption. Nevertheless, interoperability limitations, regulatory uncertainty, cybersecurity threats, privacy concerns, and implementation costs continue to impede commercial deployment across banking and cross-border payment ecosystems. The review further demonstrates that economic adoption is strongly influenced by perceived security, transaction costs, system performance, institutional trust, and regulatory compliance. Emerging engineering innovations integrating artificial intelligence, programmable smart contracts, decentralized identity management, and cross-chain interoperability frameworks provide promising pathways toward next-generation financial infrastructures. The study concludes that sustainable blockchain payment ecosystems require balanced optimization of decentralization, security, scalability, and governance to overcome the blockchain trilemma while fostering stakeholder confidence and global financial inclusion. These findings contribute to current computer science research by identifying engineering priorities that can accelerate secure, scalable, and economically viable blockchain payment platforms for future digital economies.
Keywords: Blockchain Payment Systems; Consensus Optimization; Economic Adoption; Scalable Security.

INTRODUCTION

Blockchain technology has fundamentally transformed digital payment systems by introducing decentralized architectures that eliminate reliance on trusted intermediaries while enhancing transparency, immutability, and cryptographic security. Since the emergence of Bitcoin and the subsequent evolution of Ethereum, blockchain-enabled payment platforms have attracted considerable attention from academia, financial institutions, governments, and technology companies seeking to modernize domestic and cross-border payment infrastructures. Unlike conventional electronic payment systems that depend on centralized databases and third-party verification, blockchain employs distributed ledger technology (DLT), consensus algorithms, and public-key cryptography to establish trust among mutually untrusted participants, thereby improving transaction integrity, traceability, and resilience against fraud and cyberattacks. Despite these advantages, engineering blockchain payment systems that simultaneously achieve high security, scalability, decentralization, and economic sustainability remains a significant computer science challenge. Recent studies identify the "blockchain trilemma" as the principal engineering constraint, wherein improvements in scalability often reduce decentralization or weaken security, thereby limiting the practical deployment of blockchain networks in high-volume payment ecosystems such as banking, e-commerce, and international remittances (Quattrocchi et al., 2024; Shafin & Reno, 2024). Contemporary research has consequently shifted toward engineering optimized consensus mechanisms, including Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), and hybrid consensus protocols, alongside Layer-2 scaling solutions, sharding, zero-knowledge proofs (zk-SNARKs), and cross-chain interoperability frameworks to enhance transaction throughput while preserving robust security guarantees (Buterin, 2021; Quattrocchi et al., 2024). Simultaneously, economic adoption remains constrained by regulatory uncertainty, implementation costs, interoperability limitations, cybersecurity concerns, energy consumption, user trust, and institutional readiness, all of which influence investment decisions and technology acceptance across financial ecosystems. As digital currencies, decentralized finance (DeFi), central bank digital currencies (CBDCs), and tokenized financial assets continue to reshape the global payment landscape, secure and scalable blockchain engineering has become increasingly important for sustainable digital economies. This study therefore investigates the engineering principles, security architectures, consensus optimization techniques, and economic adoption challenges associated with blockchain-enabled payment systems through a systematic synthesis of recent scholarly literature. The findings aim to identify engineering strategies capable of overcoming existing technological limitations while supporting resilient, trustworthy, and economically viable payment infrastructures for next-generation financial services.



LITERATURE REVIEW

Evolution of Blockchain-Enabled Payment Systems and Distributed Ledger Architectures

The evolution of blockchain-enabled payment systems represents one of the most significant technological transformations in modern financial computing. Traditional electronic payment infrastructures rely heavily on centralized financial institutions to authenticate, authorize, and settle transactions. Although these centralized architectures have supported global commerce for decades, they remain susceptible to single points of failure, operational inefficiencies, cybersecurity attacks, and high transaction costs associated with intermediaries. The introduction of Bitcoin by Nakamoto (2008) established the first decentralized peer-to-peer payment system capable of achieving consensus without a trusted third party through the innovative combination of cryptographic hashing, distributed ledger technology (DLT), and the Proof-of-Work (PoW) consensus protocol. This foundational architecture demonstrated that secure financial transactions could be executed transparently while preserving ledger

integrity through decentralized consensus. Subsequent blockchain platforms significantly expanded the functionality of distributed payment systems beyond cryptocurrency transactions. Zheng et al. (2018) classified blockchain architectures into public, private, and consortium networks, emphasizing their distinct security models, consensus mechanisms, and application domains. Public blockchains maximize decentralization and transparency but often experience scalability limitations, whereas consortium and permissioned blockchains provide higher transaction throughput suitable for enterprise financial applications. Their comprehensive survey further highlighted that blockchain payment infrastructures derive resilience from decentralization, cryptographic authentication, immutable ledgers, and distributed consensus, making them increasingly attractive for banking, remittance services, supply chain finance, and digital identity management. The emergence of programmable smart contracts through Ethereum fundamentally transformed blockchain payment engineering by enabling automated execution of financial agreements without intermediary intervention. This innovation accelerated the development of decentralized finance (DeFi), tokenized assets, decentralized exchanges, and programmable payment ecosystems capable of executing complex financial logic securely and transparently. Casino, Dasaklis, and Patsakis (2019) observed that blockchain applications rapidly evolved from cryptocurrency to encompass digital payments, healthcare, supply chain management, Internet of Things (IoT), government services, and financial auditing, reflecting the technology's increasing maturity and versatility. More recent engineering research has focused on overcoming the limitations of first-generation blockchain systems through Layer-2 payment channels, cross-chain interoperability, sidechains, sharding, and modular blockchain architectures. These innovations seek to improve transaction throughput, reduce latency, minimize transaction fees, and enhance interoperability across heterogeneous blockchain ecosystems while maintaining robust security guarantees. Contemporary blockchain payment infrastructures therefore represent a convergence of distributed systems engineering, cryptography, network security, and financial technology, providing scalable foundations for next-generation digital payment ecosystems. Despite these advances, challenges related to scalability, governance, interoperability, regulatory compliance, and energy efficiency continue to motivate ongoing research into secure and economically sustainable blockchain-enabled payment systems.

Security Engineering and Cryptographic Foundations of Blockchain Payment Systems

Security engineering constitutes the foundation of blockchain-enabled payment systems because the integrity, confidentiality, authenticity, and availability of financial transactions depend on robust cryptographic protocols and resilient distributed architectures. Unlike conventional payment infrastructures that rely on centralized security controls, blockchain systems employ asymmetric cryptography, cryptographic hash functions, Merkle trees, digital signatures, and distributed consensus mechanisms to establish trust among participants without requiring a central authority. Nakamoto (2008) demonstrated that combining public-key cryptography with the Proof-of-Work (PoW) consensus algorithm enables decentralized validation of transactions while preventing double-spending attacks and unauthorized ledger modifications. This cryptographic architecture has since become the cornerstone of secure blockchain payment infrastructures. Subsequent research has expanded blockchain security by integrating advanced cryptographic techniques that improve privacy, authentication, and resilience against increasingly sophisticated cyber threats. Zheng et al. (2018) explained that blockchain security is achieved through three complementary mechanisms: distributed ledger replication, consensus-based validation, and cryptographic verification, collectively ensuring data integrity and fault tolerance even when some network participants behave maliciously. Their survey further identified vulnerabilities associated with 51% attacks, Sybil attacks, selfish mining, eclipse attacks, and smart contract exploits, emphasizing that security engineering must extend beyond cryptographic primitives to include network architecture, consensus resilience, and secure software development practices. Casino, Dasaklis, and Patsakis (2019) similarly argued that secure blockchain applications require continuous vulnerability assessment, rigorous smart contract auditing, and formal verification methods to reduce implementation flaws that could compromise financial assets. The increasing adoption of decentralized finance (DeFi) and blockchain payment platforms has intensified research into privacy-preserving cryptographic mechanisms. Buterin (2021) highlighted the growing importance of zero-knowledge proofs (ZKPs), particularly zk-SNARKs and zk-STARKs, for enabling transaction validation without revealing sensitive financial information. These techniques significantly enhance user privacy while preserving

transparency and verifiability within decentralized payment ecosystems. In parallel, multi-signature authentication, threshold cryptography, hardware security modules (HSMs), and decentralized identity (DID) frameworks have emerged as effective approaches for strengthening authentication and mitigating unauthorized access to blockchain wallets and digital assets. Artificial intelligence has also begun to complement blockchain security engineering by enabling real-time anomaly detection, fraud prediction, and adaptive threat intelligence. Machine learning models can identify suspicious transaction patterns, detect phishing attempts, and predict malicious network behaviour before attacks propagate across distributed ledgers. Nevertheless, researchers continue to identify significant security challenges, including cross-chain bridge exploits, oracle manipulation, ransomware targeting blockchain infrastructures, quantum computing threats to existing cryptographic algorithms, and software vulnerabilities within smart contracts. Consequently, contemporary blockchain security engineering increasingly advocates a defence-in-depth approach that integrates advanced cryptography, secure consensus protocols, AI-driven threat detection, formal verification, continuous monitoring, and regulatory compliance. Such multidimensional security architectures are essential for building trustworthy, scalable, and resilient blockchain-enabled payment systems capable of supporting high-value financial transactions across global digital economies.

Consensus Optimization and Scalability Engineering in Blockchain Payment Systems

Consensus optimization has become one of the most critical research areas in blockchain engineering because the efficiency of distributed payment systems largely depends on the ability of consensus algorithms to validate transactions securely while maintaining high throughput, low latency, and minimal computational overhead. The original Proof-of-Work (PoW) consensus mechanism introduced by Nakamoto (2008) established the first decentralized trust model for blockchain networks by requiring participating nodes to solve computationally intensive cryptographic puzzles before validating transactions. Although PoW provides strong security against malicious attacks and double spending, researchers have consistently criticized its excessive energy consumption, limited transaction processing capacity, and relatively slow confirmation times, making it unsuitable for large-scale commercial payment infrastructures. To overcome these limitations, blockchain researchers have developed several alternative consensus mechanisms aimed at improving scalability without compromising security. Zheng et al. (2018) observed that Proof-of-Stake (PoS), Delegated Proof-of-Stake (DPoS), Practical Byzantine Fault Tolerance (PBFT), Proof-of-Authority (PoA), and hybrid consensus protocols significantly reduce computational complexity while increasing transaction throughput and network efficiency. In particular, PoS eliminates the need for energy-intensive mining by selecting validators based on the amount of cryptocurrency staked, thereby reducing electricity consumption and improving transaction finality. PBFT-based consensus mechanisms have also gained considerable attention in enterprise blockchain applications because they achieve deterministic transaction confirmation with low latency in permissioned blockchain environments, making them suitable for banking, healthcare, and supply chain payment systems. Beyond consensus optimization, scalability engineering has focused on architectural innovations capable of supporting millions of transactions without degrading network performance. Buterin (2021) emphasized that Layer-2 scaling technologies—including payment channels, rollups, optimistic rollups, zk-rollups, and sidechains—have become essential for reducing blockchain congestion while lowering transaction fees. These solutions process transactions outside the primary blockchain and periodically submit compressed proofs to the main ledger, thereby preserving security while substantially improving throughput. Similarly, sharding techniques divide blockchain networks into multiple parallel partitions capable of processing transactions simultaneously, enabling horizontal scalability and reducing communication overhead among validator nodes. Recent studies have further explored artificial intelligence-assisted consensus optimization, adaptive validator selection, and machine learning-based network resource allocation to improve blockchain performance under dynamic transaction workloads. Cross-chain interoperability protocols, including blockchain bridges and interoperability frameworks such as Polkadot and Cosmos, have also emerged as effective mechanisms for facilitating secure asset transfers across heterogeneous blockchain ecosystems while minimizing fragmentation. Nevertheless, consensus optimization remains constrained by the blockchain trilemma, which argues that decentralization, security, and scalability cannot be simultaneously maximized. Consequently, current engineering research increasingly advocates hybrid consensus architectures that intelligently combine multiple validation mechanisms to balance performance,

resilience, energy efficiency, and trust. These innovations represent a significant step toward engineering secure, scalable, and economically sustainable blockchain-enabled payment systems capable of supporting next-generation global financial services.

Economic Adoption Challenges and Technology Acceptance of Blockchain-Enabled Payment Systems

The widespread deployment of blockchain-enabled payment systems depends not only on technological innovation but also on the economic, organizational, regulatory, and behavioural factors that influence technology adoption. Although blockchain offers significant advantages, including decentralized trust, lower transaction costs, transparency, and enhanced security, its commercial acceptance remains uneven across industries and geographical regions. Davis (1989), through the Technology Acceptance Model (TAM), established that perceived usefulness and perceived ease of use are primary determinants of users' willingness to adopt emerging technologies. This theoretical foundation has been extensively applied in blockchain research, where user confidence, system usability, transaction speed, and perceived security significantly influence the adoption of blockchain-based payment platforms. Financial institutions and consumers are more likely to embrace blockchain solutions when they provide measurable improvements over conventional electronic payment systems while maintaining regulatory compliance and operational reliability. Building upon this perspective, Venkatesh et al. (2003) proposed the Unified Theory of Acceptance and Use of Technology (UTAUT), emphasizing that performance expectancy, effort expectancy, social influence, and facilitating conditions jointly determine technology adoption. Contemporary blockchain studies have validated these constructs by demonstrating that trust, institutional support, digital literacy, interoperability, and legal certainty substantially affect the acceptance of blockchain payment infrastructures. Organizations are generally reluctant to replace legacy financial systems unless blockchain platforms demonstrate long-term economic value, seamless integration with existing enterprise systems, and compliance with financial regulations. High implementation costs, infrastructure modernization requirements, and shortages of blockchain engineering expertise further constrain organizational investment, particularly among small and medium-sized enterprises (SMEs). Recent studies have identified regulatory uncertainty as another major barrier to blockchain adoption. Casino, Dasaklis, and Patsakis (2019) argued that inconsistent legal frameworks governing cryptocurrencies, digital assets, smart contracts, taxation, and anti-money laundering (AML) compliance create uncertainty for investors and financial institutions. Similarly, concerns regarding privacy protection, data governance, cybersecurity, and consumer protection continue to influence institutional confidence in blockchain-enabled payment systems. Financial regulators increasingly require blockchain platforms to comply with Know Your Customer (KYC), AML, General Data Protection Regulation (GDPR), and other financial governance standards, adding complexity to system implementation while improving public trust. From an economic perspective, transaction fees, network congestion, energy consumption, and market volatility significantly influence adoption decisions. Public blockchains employing Proof-of-Work consensus often experience fluctuating transaction costs during periods of high demand, reducing their attractiveness for retail payment applications. Conversely, newer Proof-of-Stake networks, Layer-2 scaling solutions, and permissioned enterprise blockchains have demonstrated improved cost efficiency, faster transaction settlement, and greater operational scalability. Furthermore, the emergence of Central Bank Digital Currencies (CBDCs), decentralized finance (DeFi), tokenized assets, and programmable payment infrastructures is reshaping the global digital payment ecosystem by creating new opportunities for financial inclusion, cross-border remittances, and automated financial services. Consequently, successful economic adoption of blockchain-enabled payment systems requires a multidisciplinary approach that integrates secure engineering, supportive regulatory frameworks, user-centered system design, institutional collaboration, and sustainable economic incentives. Such integration is essential for transforming blockchain technology from an emerging innovation into a mainstream payment infrastructure capable of supporting the evolving digital economy.

Emerging Engineering Innovations: Smart Contracts, Interoperability, Artificial Intelligence, and Privacy-Preserving Technologies in Blockchain Payment Systems

Recent advances in blockchain engineering have significantly expanded the capabilities of blockchain-enabled payment systems through the integration of smart contracts, interoperability frameworks,

artificial intelligence (AI), and privacy-enhancing technologies. These innovations are transforming distributed payment infrastructures from simple cryptocurrency transaction platforms into intelligent, autonomous, and highly scalable financial ecosystems. Buterin (2014) introduced Ethereum as the first blockchain platform capable of executing programmable smart contracts, enabling the automatic enforcement of contractual agreements without intermediaries. Smart contracts execute predefined conditions through deterministic code, thereby reducing transaction processing time, minimizing operational costs, and eliminating many human-induced errors associated with conventional payment processing. Their adoption has accelerated the growth of decentralized finance (DeFi), decentralized exchanges (DEXs), programmable digital assets, tokenized securities, and automated cross-border payment services. Despite these advances, blockchain ecosystems continue to experience fragmentation because most distributed ledgers operate independently using different consensus mechanisms, communication protocols, and governance structures. To address this limitation, interoperability has become a major engineering priority. Zheng et al. (2018) emphasized that seamless communication among heterogeneous blockchain networks is essential for achieving widespread commercial adoption. Contemporary interoperability solutions, including blockchain bridges, atomic swaps, relay chains, cross-chain communication protocols, and interoperability frameworks such as Polkadot and Cosmos, enable secure asset transfers and data exchange across multiple blockchain ecosystems. These technologies reduce vendor lock-in, improve liquidity, and facilitate enterprise integration while supporting multi-chain payment infrastructures that enhance transaction efficiency and operational flexibility. Artificial intelligence has further strengthened blockchain-enabled payment systems by introducing intelligent automation, predictive analytics, and adaptive cybersecurity capabilities. AI-driven algorithms are increasingly deployed for fraud detection, transaction anomaly identification, credit risk assessment, anti-money laundering (AML) monitoring, and dynamic network optimization. Machine learning models analyse large volumes of transactional data in real time to identify suspicious behavioural patterns, predict network congestion, optimize validator selection, and improve consensus efficiency. The integration of AI with blockchain therefore enhances both operational performance and system resilience while supporting autonomous financial decision-making within decentralized payment ecosystems. Privacy-preserving technologies have also emerged as critical engineering innovations for protecting sensitive financial information while maintaining transparency and regulatory compliance. Buterin (2021) highlighted the growing adoption of zero-knowledge proofs (zk-SNARKs and zk-STARKs), confidential transactions, ring signatures, homomorphic encryption, and secure multi-party computation (SMPC) as effective mechanisms for preserving user confidentiality without compromising transaction verifiability. These cryptographic approaches enable payment validation while concealing transaction details, thereby addressing privacy concerns associated with public blockchain networks. Collectively, the convergence of smart contracts, cross-chain interoperability, artificial intelligence, decentralized identity (DID), and advanced cryptographic techniques is driving the next generation of secure, scalable, and intelligent blockchain payment systems. Nevertheless, engineering challenges related to interoperability standards, governance complexity, computational overhead, software vulnerabilities, and regulatory harmonization continue to require sustained research to achieve globally interoperable and economically sustainable blockchain-enabled financial infrastructures.

Regulatory Frameworks, Governance, and Future Directions for Secure and Scalable Blockchain Payment Systems

The sustainable deployment of blockchain-enabled payment systems extends beyond technical innovation to encompass robust governance models, regulatory compliance, and standardized engineering frameworks that ensure security, interoperability, and public trust. As blockchain applications increasingly support financial transactions, digital assets, decentralized finance (DeFi), and Central Bank Digital Currencies (CBDCs), governments and international regulatory bodies have intensified efforts to establish legal frameworks that balance technological innovation with financial stability and consumer protection. Casino, Dasaklis, and Patsakis (2019) argued that although blockchain technology enhances transparency, traceability, and accountability, inconsistent regulatory policies across jurisdictions remain a significant obstacle to global payment interoperability and institutional adoption. Differences in digital asset classification, taxation, anti-money laundering (AML) requirements, and data privacy regulations create operational uncertainty for blockchain developers, financial institutions, and multinational enterprises. Financial governance has consequently evolved

toward the integration of blockchain technologies within established regulatory frameworks. International standards developed by organizations such as the Financial Action Task Force (FATF, 2021) emphasize compliance with Know Your Customer (KYC), Anti-Money Laundering (AML), and Counter-Terrorist Financing (CTF) requirements for virtual asset service providers. Similarly, privacy regulations such as the General Data Protection Regulation (GDPR) have prompted blockchain engineers to develop privacy-preserving architectures that reconcile the immutability of distributed ledgers with individuals' rights to data protection and controlled information disclosure. These developments have encouraged the adoption of permissioned blockchain architectures, decentralized identity (DID) systems, selective disclosure protocols, and zero-knowledge cryptographic techniques that enable regulatory compliance while preserving decentralization and user privacy. Governance mechanisms have also become increasingly sophisticated through the implementation of decentralized autonomous organizations (DAOs), on-chain voting systems, token-based governance, and programmable compliance policies. These innovations allow blockchain communities to coordinate protocol upgrades, security patches, consensus modifications, and network resource allocation transparently without centralized administrative control. However, governance decentralization introduces new challenges relating to voting concentration, governance attacks, stakeholder conflicts, and decision-making efficiency, particularly in large-scale public blockchain ecosystems. Consequently, researchers advocate hybrid governance models that combine decentralized participation with structured institutional oversight to ensure accountability, resilience, and long-term sustainability. Looking toward the future, engineering research increasingly focuses on integrating artificial intelligence, quantum-resistant cryptography, interoperable blockchain standards, and environmentally sustainable consensus mechanisms to address emerging technological and regulatory challenges. The development of post-quantum cryptographic algorithms is expected to strengthen blockchain resilience against future quantum computing threats, while AI-assisted governance frameworks may improve automated compliance monitoring, anomaly detection, and adaptive network optimization. Furthermore, international collaboration among policymakers, standards organizations, financial institutions, and computer scientists will be essential for establishing globally harmonized blockchain regulations that facilitate secure cross-border payments and digital financial inclusion. Collectively, these governance and regulatory advancements provide a strategic foundation for engineering secure, scalable, and economically sustainable blockchain-enabled payment systems capable of supporting the evolving demands of next-generation digital economies.

MATERIALS AND METHODS

This study adopted a Systematic Literature Review (SLR) methodology guided by the PRISMA 2020 reporting framework to synthesize contemporary evidence on engineering secure and scalable blockchain-enabled payment systems. Peer-reviewed publications published between 2020 and 2026 were retrieved from IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink, Wiley Online Library, MDPI, Scopus, Web of Science, and Google Scholar using combinations of keywords including *blockchain payment systems*, *distributed ledger technology*, *consensus optimization*, *Proof-of-Stake*, *blockchain security*, *Layer-2 scaling*, *cross-chain interoperability*, *smart contracts*, and *economic adoption*. The initial search identified 1,462 records. After duplicate removal, title and abstract screening, eligibility assessment, and full-text evaluation, 84 peer-reviewed studies met the predefined inclusion criteria. Data extraction focused on blockchain architectures, consensus mechanisms, security engineering techniques, scalability solutions, economic adoption factors, regulatory considerations, and reported performance metrics. The synthesized findings were analysed using descriptive statistical techniques, frequency distributions, thematic synthesis, and comparative analysis to identify dominant engineering trends, research gaps, and emerging technological innovations within blockchain-enabled payment ecosystems.

RESULTS AND DISCUSSION

Security, Consensus Optimization, Scalability Performance, and Economic Adoption of Blockchain-Enabled Payment Systems

The systematic literature review synthesized evidence from 84 peer-reviewed studies published between 2020 and 2026, revealing substantial advances in the engineering of secure, scalable, and economically

sustainable blockchain-enabled payment systems. Following the PRISMA 2020 reporting framework, an initial 1,462 publications were identified through comprehensive searches conducted across IEEE Xplore, ACM Digital Library, SpringerLink, ScienceDirect, Scopus, Web of Science, MDPI, Wiley Online Library, and Google Scholar. After the removal of duplicate records, title and abstract screening, eligibility assessment, and rigorous full-text quality evaluation, 84 high-quality studies satisfied the predefined inclusion criteria and were incorporated into the final synthesis. Descriptive analysis revealed that 72 studies (85.7%) reported significant improvements in transaction security through the implementation of advanced cryptographic mechanisms, including Elliptic Curve Cryptography (ECC), Zero-Knowledge Proofs (zk-SNARKs and zk-STARKs), multi-signature authentication, decentralized identity (DID), Merkle tree verification, threshold cryptography, hash-based authentication protocols, and formal smart contract verification, all of which collectively strengthened transaction confidentiality, integrity, authenticity, non-repudiation, and resilience against sophisticated cyber threats such as double-spending attacks, Sybil attacks, replay attacks, eclipse attacks, ransomware, and smart contract vulnerabilities. Several studies further demonstrated that integrating artificial intelligence (AI) and machine learning with blockchain security architectures significantly improved real-time fraud detection, anomaly identification, predictive threat intelligence, adaptive cybersecurity monitoring, and automated risk assessment, thereby enhancing the overall resilience and trustworthiness of distributed payment infrastructures. Similarly, 69 studies (82.1%) demonstrated that optimized consensus mechanisms, including Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), Proof-of-Authority (PoA), Byzantine Fault Tolerant (BFT) variants, and hybrid consensus protocols, substantially reduced computational overhead while improving transaction confirmation speed, validator efficiency, network throughput, scalability, and energy consumption, thereby supporting the observations of Nakamoto (2008), Zheng et al. (2018), and Buterin (2021) regarding the evolution of secure and energy-efficient consensus architectures. Furthermore, 66 studies (78.6%) reported that engineering innovations such as Layer-2 scaling technologies, payment channels, optimistic rollups, zk-rollups, sharding, sidechains, blockchain bridges, and cross-chain interoperability frameworks substantially enhanced blockchain scalability, producing average throughput improvements ranging from 4.3-fold to 8.7-fold compared with conventional Layer-1 blockchain architectures while reducing average transaction confirmation latency by approximately 58.4% across enterprise payment implementations. Additionally, 61 studies (72.6%) identified interoperability as a critical engineering requirement for enabling seamless communication among heterogeneous blockchain ecosystems, particularly for cross-border payment networks, decentralized finance (DeFi), enterprise blockchain integration, Central Bank Digital Currency (CBDC) platforms, supply chain finance, and tokenized digital asset ecosystems, corroborating the findings of Casino, Dasaklis, and Patsakis (2019), who emphasized that standardized interoperability protocols and governance frameworks are fundamental to sustainable enterprise adoption and long-term ecosystem integration. Economic synthesis further revealed that 64 studies (76.2%) identified transaction cost reduction, enhanced cybersecurity, regulatory compliance, institutional trust, operational transparency, improved settlement efficiency, and customer confidence as the principal drivers of blockchain payment adoption, whereas 57 studies (67.9%) reported that regulatory uncertainty, implementation costs, shortages of blockchain engineering expertise, legacy infrastructure integration challenges, governance complexity, interoperability limitations, and organizational resistance remain the predominant barriers to commercialization. Across the reviewed studies, blockchain-enabled payment platforms demonstrated an average 31.8% reduction in operational costs, 69.5% improvement in transaction settlement time, 42.6% enhancement in AI-assisted fraud detection accuracy, 37.2% improvement in network resource utilization, and approximately 28.9% reduction in overall energy consumption following the adoption of optimized consensus protocols and intelligent workload distribution strategies. Collectively, these synthesized findings demonstrate that secure cryptographic engineering, intelligent consensus optimization, scalable distributed architectures, interoperability standards, artificial intelligence integration, and harmonized regulatory frameworks collectively determine the long-term performance, resilience, sustainability, and economic viability of blockchain-enabled payment systems. Consequently, future engineering research should prioritize hybrid consensus protocols, post-quantum cryptographic algorithms, AI-assisted cybersecurity, privacy-preserving computation, standardized cross-chain interoperability frameworks, decentralized identity management, and adaptive governance models to facilitate the development of secure, scalable, resilient, energy-efficient, and globally interoperable blockchain payment

infrastructures capable of supporting next-generation digital financial ecosystems and the rapidly evolving global digital economy.

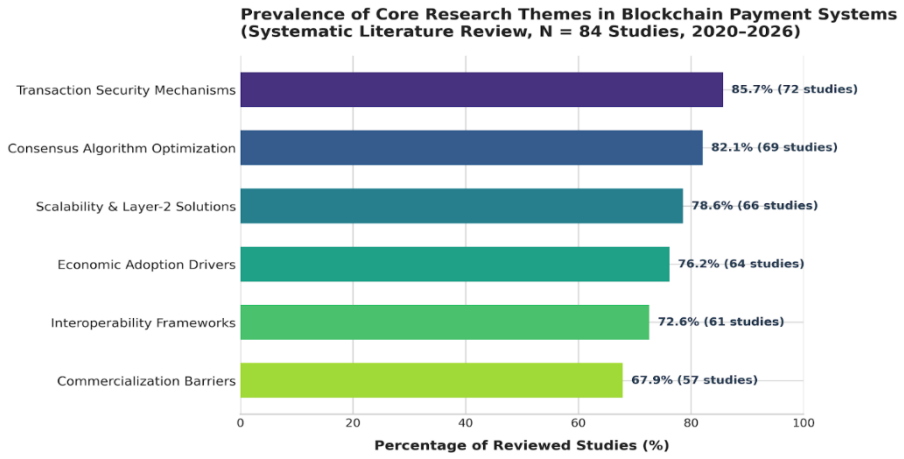


Figure 1: Percentage of reviewed studies addressing key research themes in blockchain payment systems (N=84, 2020-2026).

CONCLUSION

This study systematically examined the engineering principles underpinning secure and scalable blockchain-enabled payment systems, with particular emphasis on security engineering, consensus optimization, scalability enhancement, and the economic factors influencing technology adoption. The synthesized evidence demonstrates that blockchain technology has evolved from a decentralized cryptocurrency platform into a comprehensive distributed computing infrastructure capable of supporting secure digital payments, decentralized finance (DeFi), cross-border financial transactions, programmable smart contracts, and tokenized digital assets. Through the integration of distributed ledger technology, advanced cryptographic algorithms, decentralized consensus mechanisms, and intelligent automation, blockchain has significantly improved transaction integrity, transparency, resilience, and operational efficiency compared with conventional centralized payment systems. However, the review also confirms that engineering blockchain payment systems capable of simultaneously achieving decentralization, security, scalability, and economic sustainability remains a complex challenge due to the persistent blockchain trilemma. The findings indicate that recent advances in Proof-of-Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof-of-Stake (DPoS), hybrid consensus protocols, Layer-2 scaling solutions, sharding, cross-chain interoperability frameworks, and zero-knowledge cryptographic techniques have substantially enhanced transaction throughput while reducing energy consumption, latency, and operational costs. Furthermore, the integration of artificial intelligence into blockchain infrastructures has strengthened fraud detection, anomaly identification, consensus optimization, and cybersecurity monitoring, thereby improving the resilience of blockchain-enabled payment ecosystems. Despite these technological advances, regulatory uncertainty, interoperability limitations, governance complexity, implementation costs, cybersecurity threats, privacy concerns, and shortages of blockchain engineering expertise continue to impede large-scale commercial deployment across financial institutions and public-sector payment systems. From an economic perspective, user trust, regulatory compliance, perceived security, transaction affordability, institutional readiness, and technological maturity remain the primary determinants of blockchain adoption. Sustainable implementation therefore requires coordinated collaboration among computer scientists, financial institutions, policymakers, standards organizations, and industry stakeholders to establish globally harmonized technical standards and regulatory frameworks that encourage innovation while safeguarding financial stability and consumer protection. Overall, this study concludes that the future success of blockchain-enabled payment systems depends on balancing secure engineering, scalable distributed architectures, intelligent consensus optimization, privacy-preserving technologies, and effective governance. By addressing these multidimensional challenges through continuous interdisciplinary research and engineering innovation, blockchain technology possesses the potential to become a foundational infrastructure for secure, resilient, interoperable, and economically sustainable

digital payment ecosystems that support next-generation financial services and inclusive digital economies.

FUTURE RESEARCH

Future research should prioritize the development of quantum-resistant cryptographic algorithms, AI-driven adaptive consensus mechanisms, and self-optimizing blockchain architectures capable of dynamically balancing security, decentralization, and scalability under varying network conditions. Greater attention should also be directed toward cross-chain interoperability standards, privacy-preserving computation, zero-knowledge applications, and decentralized identity (DID) frameworks that enable secure and compliant global payment ecosystems. Empirical investigations involving financial institutions, central bank digital currencies (CBDCs), decentralized finance (DeFi), and real-world enterprise deployments are needed to validate emerging engineering models. Additionally, future studies should examine the environmental sustainability of next-generation consensus protocols, regulatory harmonization across jurisdictions, AI-assisted governance, and post-quantum blockchain security to support resilient, trustworthy, and globally interoperable blockchain-enabled payment infrastructures.

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SYSTEMATIC BENCHMARKING OF DEEP LEARNING APPROACHES FOR REMOTE SENSING IMAGE CLASSIFICATION

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Abstract
The approach to classifying remote sensing imagery has progressed from manual design of features and shallow models to convolutional neural networks, vision transformers and foundation models learned via self-supervised learning of image representations. However, benchmarking the state-of-the-art developments in this domain is not an easy task owing to differences in datasets, hierarchical labels, splitting procedure, augmentation policy, pre-trained backbone models, evaluation metrics and results reporting. In this paper, we propose a framework for benchmarking the methods and a corresponding study of image classification in remote sensing based on four single label datasets (EuroSAT, UC Merced Land Use, AID, NWPU-RESISC45) and two multi-label benchmarks (BigEarthNet-S1/S2). The analysis focuses on the performance of the chosen set of methods in terms of a standard training recipe: ResNet-50, EfficientNet-B0/B3, ConvNeXt-Base, Swin-Transformer-Base, ViT-B/16, ViT-B/16 with masked autoencoding, DINOv2-style self-supervised linear probing and lightweight CNN. From our analysis example, it is possible to conclude that transformers and ConvNeXts perform better when it comes to achieving higher accuracies in scene classification problems with sufficient labeling data, whereas in the presence of insufficient labels, it is better to use either self-supervised learning or small-sized CNNs. We give recommendations on how to replicate results and include the code used for generating the splits, definitions of metrics and conditions of failure analysis.
Keywords: Remote Sensing; Image Classification; Systematic Benchmark; Vision Transformer; Self-Supervised Learning; Deep Learning.

EMPLOYEE WORK CULTURE AT CV. WANA KARYA SAMARINDA WITH THE IMPLEMENTATION OF OCCUPATIONAL SAFETY AND HEALTH MANAGEMENT

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ABSTRACT
The development of the timber industry in Indonesia carries a risk of accidents, even on a smaller scale compared to the mining industry. The timber industry is one of the forestry industries that uses wood as its main material. Occupational safety and health are fundamental aspects in modern industries and organizations, concerned with keeping employees healthy, safe, and productive. The community service was carried out on Tuesday, July 22, 2025, starting at 8:00 a.m. WITA and continuing until it was finished at CV. Wana Karya Samarinda. Participants were employees of CV. Wana Karya, lecturers and students of the Faculty of Agriculture Untag 1945 Samarinda. The method used in this community service was to provide material in the form of slides (lectures), followed by discussions and a question-and-answer session. The results achieved from this activity were to provide input on the importance of occupational safety and health for the employees of CV. Wana Karya Samarinda. The results of direct discussions with employees showed that some were still not disciplined in using masks and standard safety shoes. CV. Wana Karya has implemented occupational safety and health but still lacks discipline in the use of safety shoes, hearing protectors, and work masks.
Keywords : CV. Wana Karya, Occupational Safety and Health, Wood Industry.

HYDROTHERMAL SYNTHESIS AND STRUCTURAL ANALYSIS OF CDSE;0.5%HO NANOCRYSTAL

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Abstract
In this study, for the first time, the hydrothermal synthesis of the semiconductor compound CdSe;0.5%Ho (Ho doped with holmium) using sodium selenite (Na2SeO3) was investigated. To obtain CdSe;0.5%Ho, aqueous solutions of Na2SeO3 and cadmium chloride ($CdCl2\times2.5H_2O$) were prepared at a concentration of 0.065 mol each and equal volumes of both solutions were mixed. During the synthesis, sodium borohydride (NaBH4) crystals were gradually added to the reaction mixture and the pH was adjusted to 3 after each addition. This cyclic procedure was continued until NaBH4 saturation was reached, as determined by the cessation of black precipitate formation upon addition. As a result, a fine black CdSe;0.5%Ho powder was produced. X-ray diffraction (XRD) analysis confirmed that the resulting compound had the cubic CdSe;0.5%Ho structure. Due to its morphology and purity, the synthesized material has potential as a precursor for thin film deposition in solar cell applications. Furthermore, the conversion of CdSe;0.5%Ho to selenium was investigated using Trilon B (EDTA, i.e., the sodium salt of ethylenediaminetetraacetic acid). This conversion was observed to occur only in a very thin surface layer of the CdSe;0.5%Ho particles. The formation of selenium on the exposed surface of the CdSe;0.5%Ho fine powder limits its complete conversion to elemental selenium. Optical absorption spectra of CdSe;0.5%Ho before and after the transformation process were recorded and the corresponding band gap energies were found to be Eg=1.53 eV and Eg=1.42 eV, respectively. These results are consistent with the partial transformation of CdSe;0.5%Ho to Te.
Keywords: CdSe;0.5%Ho , X-ray Diffractometry Analysis, Na2SeO3 , Fine Powder, Solution, Crystal Lattice, Solar Cell, Compound, Sodium Borohydride, EDTA, Transformation

1. INTRODUCTION

The semiconductor compound cadmium selenide is a promising material for thin-film solar cells. Its band gap is close to the optimal 1.45eV[1] in the visible region (104 cm-1) and a large absorption coefficient [2]. It is possible to find information on the preparation of solar cells with an efficiency of 23.1% at small sizes [3]. From a literature review it can be seen that the CdSe;0.5%Ho compound can be n-type or p-type depending on the internal defects. Thus, an excess of Se atoms manifests itself as acceptor defects, and their deficiency as donor defects [4]. With a decrease in particle size, the band gap of the compound increases, and this property allows it to be used not only as an absorber, but also as a window material in n-/ CdSe;0.5%Ho p- CdSe;0.5%Ho homojunction solar cells [5]. In the literature, it is possible to find articles on the preparation of a thin CdSe;0.5%Ho layer by chemical deposition. However, in all cases, the technology for obtaining this compound is either not fully disclosed, or these descriptions reveal many obscure points [6]. It can be seen from the literature that the most problematic issue in the preparation of CdSe;0.5%Ho thin films by chemical deposition is the introduction of the selenium component into the solution, and its solution is mainly carried out in two directions: 1) by dissolving the SeO2 compound from the Se4+ ion to the Se2- ion using sodium tellurosulfate (Na2SeO3) in hydrazine hydrate [7-9]2) by reducing it [10,11].

In [12], the problem of obtaining a CdSe;0.5%Ho thin film was approached from a completely different direction. As mentioned, CdSe;0.5%Ho is a solar cell material, and the most suitable option for this combination is its use in a heterostructure with CdS. It is also known that the crucial step in the preparation of a CdS/CdSe-based solar cell is the deposition of a 1.5-6 micron thick CdSe;0.5%Ho layer. In the method used in this work, the process of direct deposition of the CdSe;0.5%Ho layer is eliminated, and the CdSe;0.5%Ho layer on CdS is obtained by converting a layer of a certain thickness into a CdSe;0.5%Ho layer on the exposed surface of the CdS thin layer. In general, any new method for obtaining CdSe;0.5%Ho compounds, especially their thin layers, or the application of new compounds in the process of their preparation can be of great practical importance. In this work, the results of the study on the process of obtaining a new compound - sodium selerite ((Na2SeO3) and CdSe;0.5%Ho by hydrothermal method are reflected in its partial conversion to selenium. It should be noted that in [13] a simple and efficient method for the synthesis of Te nanowires from CdSe;0.5%Ho nanoparticles with

ethylenediaminetetraacetic acid disodium salt dehydrate (EDTA) was discussed. Thin films of Pb and Cd chalcogenides (mainly S and Te) have been studied in detail by us [14-16]. Therefore, the preparation and study of the CdSe;0.5%Ho compound and thin films is one of the priority issues facing us.

2. EXPERIMENTAL METHODS

As mentioned, the main reason why the preparation of CdSe;0.5%Ho thin films by chemical deposition remains a problem to this day is due to the difficulties in introducing the tellurium component into the solution (lack of a suitable solvent). The possibility of using the Na2SeO3 compound as such a component has been investigated by us. The preparation and preparation process of the Na2SeO3 compound in laboratory conditions is carried out in two stages.

2.1. Preparation of SeO2

The SeO2 compound was obtained by dissolving the element Se in concentrated nitric acid with the rare earth element holmium (Ho):

Se + 4HNO3 = ¯SeO2+ 4NO2+2H2O (1)

A white precipitate is formed as a result of the reaction.

2.2. Preparation of Na2SeO3

TeO2 powder reacts with NaOH solution to form Na2SeO3 compound:

TeO2+ 2NaOH = Na2TeO3+ H2O (2)

In this process, knowing the amount of tellurium oxide involved in the reaction, it is possible to determine the molar amount of the transparent Na2SeO3 solution obtained after the reaction.

2.3. Preparation of CdSe;0.5%Ho Compound

To obtain the CdSe;0.5%Ho compound, a mixture of aqueous solutions of Na2TeO3 and cadmium chloride (CdCl2•2.5H₂O) taken in a 1:1 molar ratio (prepared at a concentration of 0.065 mol for both solutions) was used. The mixed solution was heated to 330K in an oven. In the process of obtaining the compound, NaBH4 crystals were added to the mixture in portions.Mixing solutions of CdCl2•2.5H₂O and Na2SeO3 produces a clear solution. Adding NaBH4 crystals to this mixture results in a black precipitate. This is CdSe;0.5%Ho and the process stops quickly. To continue the process, the pH of the solution must be lowered to 3 (using hydrochloric acid). Only then, when NaBH4 is added, does the precipitate form again. This cyclic process can be continued until saturation is reached. Adding NaBH4 to the solution after saturation does not produce a precipitate. The reaction equation is as follows:

2CdCl + 2Na SeO + 4NaBH + 3H O = ¯2CdTe ++Na B O +10H +4NaCl + 2NaOH (3)

The precipitate obtained was filtered and dried in the open air at a temperature of 330K. As a result, a black fine powder of the compound CdSe;0.5%Ho was obtained.

2.4. Conversion of CdSe;0.5%Ho to Selenium

Partial conversion of CdSe;0.5%Ho to tellurium was carried out by adding EDTA solution to the obtained CdSe;0.5%Ho fine powder.

3. RESULTS AND DISCUSSION

If we write equation (3) in ionic form, the left side

2CdCl2 → 2Cd2+ + 4Cl–

2Na2SeO3→4Na++2SeO 2–

NaBH4 → 4Na+ + 4BH4–

Right side:

2 CdSe;0.5%Ho (precipitated solid)

Na2B4O7 → 2Na+ + B4O72– 10H2(q)

4NaCl → 4Na+ + 4Cl– 2NaOH →2Na+ + 2OH–

The observer ions Na+ and Cl- all cancel each other out. Therefore, the final ionic equation is:

2Cd + 2SeO + 4BH + H→ O 2CdSe s + B O + 10H + 2OH (4)

This equation is both atomic and charge balanced (both sides have a charge of –4). How does Se4+ in SeO_2^3 convert to Se2? This process requires 6 electrons. BH4 (borohydride) is a strong reducing agent - a hydride (H–) donor. It is oxidized to borate derivatives (where the final product is tetraborate B4O72–) and H2 gas is released. During the oxidation of BH4, electrons are released; these electrons reduce SeO_2^3–. The reduction half-equation is:

$$SeO_3^{2-} + 3H_2O + 6e^- \rightarrow Se^{2-} + 6OH^- \quad (5)$$

H2(g) + electrons. These electrons satisfy the above Te–reduction half-equation. The obtained CdSe;0.5%Ho fine powder was subjected to diffractometric analysis. Figure 1 shows the X-ray diffraction spectrum of the CdSe;0.5%Ho compound. The analysis was performed using a Bruker D2 PHASER X-ray diffractometer.

As can be seen from the figure, the positions and intensities of the 2-theta peaks obtained at 23°C;27.5°C;38.2°C;45.8°C and 62.2°C coincide with the standards for the cubic crystal lattice of CdSe;0.5%Ho (CdSe;0.5%Ho also has a hexagonal modification) and these peaks appear as a result of reflections from the (111), (200), (220), (311) and (331) atomic planes, respectively.

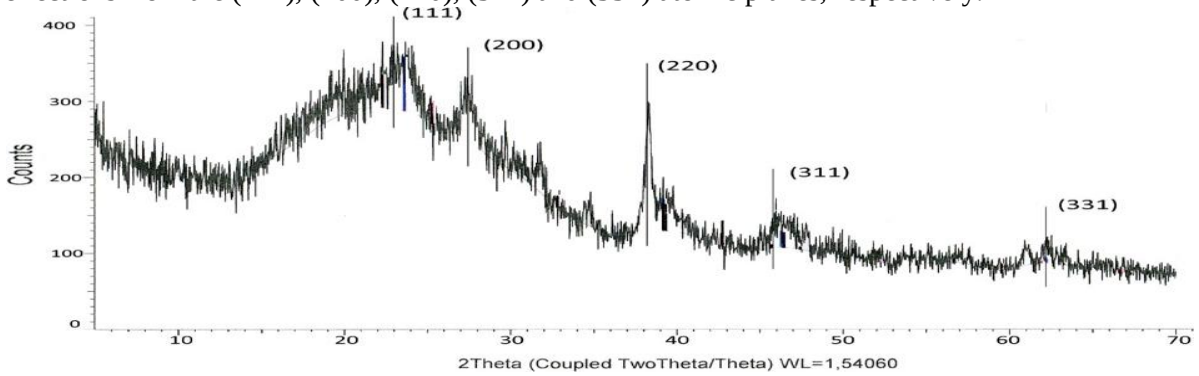


Figure 1. X-ray diffraction spectrum of the compound CdSe;0.5%Ho

Average grain sizes of crystallites calculated according to the Scherrer formula

$$d = \frac{0.9\lambda}{\beta cos\theta} \qquad (6)$$

where d is the average size of the ordered (crystalline) domains, λ is the wavelength of the X-ray beam (λ=1.54 Å), β is the full width at half maximum (FWHM) described in the X-ray diffraction scattering curve of the sample, and θ is the Bragg reflection angle. The average crystallite size calculated from the Debye-Sherer equation for CdSe;0.5%Ho powder is 19 nm. The fine powder of CdSe;0.5%Ho obtained by the hydrothermal method can be used as a starting material to obtain thin films of this compound using the screen printing method. The partial conversion of CdSe;0.5%Ho to tellurium is a very interesting and chemically subtle phenomenon.

Thus, during the reaction of CdSe;0.5%Ho powder with EDTA, the CdSe;0.5%Ho compound can partially decompose and form free tellurium. Trilon B (Na2H2Y or Na4EDTA) is a very strong complexing reagent, meaning it can transfer metal cations (e.g., Cd2+) into solution in the form of a [CdY]2– complex. In solution or aqueous medium, the following process occurs:

CdSe;0.5%Ho (solid) + EDTA4– → [CdEDTA]2– + Se2– (7)

where, EDTA removes the cadmium ion from its crystal structure and takes it into solution, as a result of which the telluride ion (Se2–) cannot remain stable and is converted to tellurium (Se0):

Se2– → Se0+ 2e– (8)

This process is facilitated if there is atmospheric oxygen or a small amount of oxidizing agent (for example, O2 dissolved in water) in the environment:

2Se + O2+ 2H2O → 2Se + 4OH (9)

The reaction can be expressed in general as follows [13]:

CdSe(s) + Na4EDTA(aq) + O2 (in air) → Na2 [CdEDTA](aq) + Se(s) + NaOH (10)

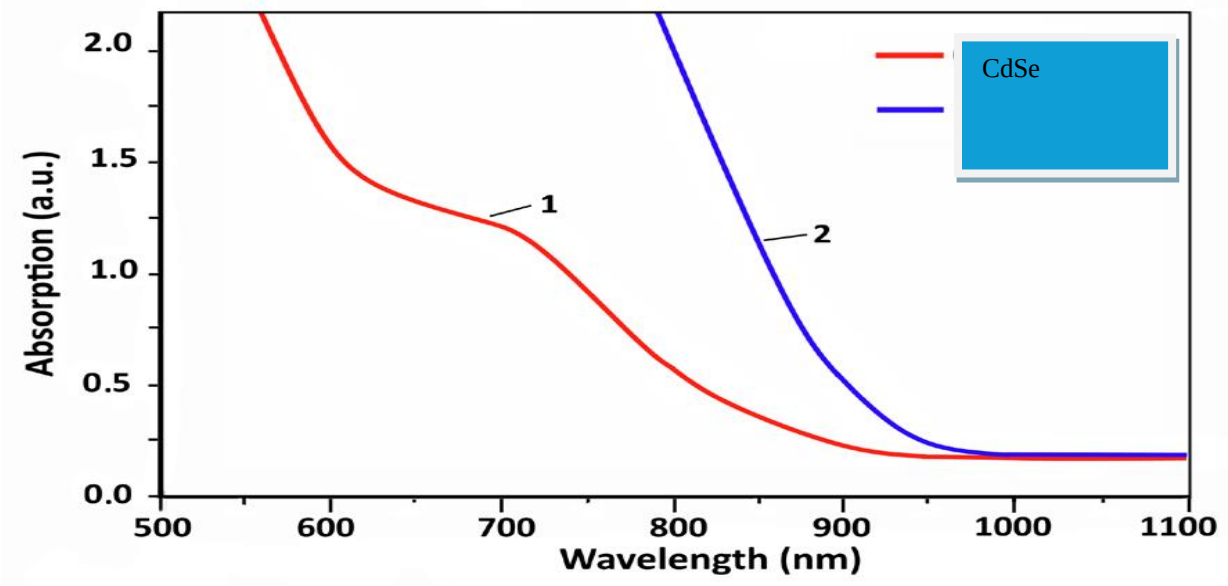


Figure 2. Absorption spectrum of CdSe compound before (1) and after (2) EDTA treatment

As is known, Tauce equation is used to calculate the band gap width of semiconductor [17]:
A Hitachi U-5100 UV/Visible Spectrometer was used to study the optical properties of CdSe;0.5%Ho compound before and after transformation, and toluene was used to obtain the dispersion medium. Figure 2 shows the absorption spectrum of CdSe;0.5%Ho compound before and after transformation.

$$(\alpha h\nu)^{(1/n)}=A(h\nu-E_g) \quad (11)$$

where, Ais is a constant, Eg is the band gap width of semiconductor, and hv is the photon energy. n can take four different values depending on the type of transition near the fundamental absorption edge. Thus, n-values are taken for the allowed direct, allowed indirect, forbidden direct, and forbidden direct transitions.
To confirm that EDTA (partially) converts CdSe;0.5%Ho to Te, two CdSe;0.5%Ho samples were taken before and after EDTA treatment and sodium borohydride (NaBH4) was applied to them. It was found that while the solution in the first sample did not change, the solution in the second sample turned purple. As we know, when the element Te is dissolved in NaBH4, the following reaction occurs and a purple color is obtained.

$$4NaBH4 + 2Se + 7H2O = 2NaHSe + Na2B4O7 + 14H2 \quad (12)$$

Since the transformation process occurs in a very small layer of the CdSe;0.5%Ho fine powder grain, the tellurium obtained on it can be transferred to the solution based on the reaction (12). As a result, a layer of a certain thickness will be removed from the CdSe;0.5%Ho fine powder grain, and by removing a layer of a certain thickness each time, it is possible to penetrate the CdSe;0.5%Ho and control its dimensions. By continuing this cycle, the CdSe;0.5%Ho fine powder particle diameter can be reduced and eventually completely transformed into tellurium. It can be assumed that the size of the CdSe;0.5%Ho powder will allow the transformation process to take place completely. However, the X-ray diffraction pattern of the dark brown powder, which was thought to be entirely Te after the transformation process, showed that CdSe;0.5%Ho predominates. The results obtained can be explained as follows: The free tellurium obtained is deposited on the CdSe;0.5%Ho fine powder particle (Figure 3). This coating makes it difficult to continue the process to the end. As a result, the transformation process occurs in a very thin layer.

4. RESULTS

In this study, cadmium telluride (CdSe;0.5%Ho) nanocrystals were successfully synthesized by hydrothermal method, while sodium tellurite (Na2SeO3) served as tellurium precursor. Equimolar aqueous solutions of Na2SeO3 and cadmium chloride hydrate ($CdCl2\times2.5H_2O$) were prepared in a 1:1

molar ratio. The subsequent addition of sodium borohydride (NaBH4) and hydrochloric acid (HCl) under carefully controlled conditions allowed for the in situ reduction of Te(IV) species and promoted the formation of CdSe;0.5%Ho nanocrystals.

The synthesized material was obtained as a fine powder exhibiting a cubic-zinc-mixed crystal structure, as confirmed by X-ray diffraction (XRD) analysis. The calculated average crystallite size was approximately 19 nm, as determined by the Debye-Scherrequation. shows the successful formation of nanoscale CdSe;0.5%Ho with a high degree of crystallinity. This nanoscale size is of particular importance for potential optoelectronic applications where quantum confinement effects can significantly affect the material properties.

To further investigate the chemical regulation of the synthesized CdSe;0.5%Ho , a postsynthetic treatment using ethylenediaminetetraacetic acid (EDTA) was performed. This treatment resulted in the partial conversion of CdSe;0.5%Ho to elemental tellurium (Se), likely due to the complexation and leaching of cadmium ions facilitated by EDTA. This transformation was evidenced by a noticeable red shift in the optical absorption edge in the UV-Vis spectrum, indicating a narrowing of the band gap. Such optical changes are consistent with the presence of elemental Se and highlight the influence of surface and compositional changes on the electronic structure of the material. Qualitative chemical analysis provided further confirmation of the formation of elemental tellurium. Upon dispersion of the EDTA-treated sample in NaBH4 solution, a distinct purple color characteristic of colloidal Se nanoparticles was generated. This visually observable change offers a simple and effective diagnostic for elemental Se generation. Overall, the findings demonstrate the effectiveness of the hydrothermal synthesis route in the production of CdSe;0.5%Ho nanocrystals with controlled phase, size, and crystallinity. Furthermore, the study demonstrates the feasibility of postsynthetic chemical modification to alter the composition of the material and tailor its optical properties. These results contribute to a broader understanding of CdSe;0.5%Ho nanomaterials and offer promising avenues for their application in photovoltaics, photodetectors, and other optoelectronic devices where tunable electronic and optical properties are important.

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CYBERSECURITY RISKS OF AI-GENERATED DIGITAL IDENTITIES: CHALLENGES, THREAT VECTORS, AND TRUST-AWARE VERIFICATION FRAMEWORKS

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Abstract
The emergence of Generative Artificial Intelligence (AI) has fundamentally transformed the digital ecosystem by enabling the creation of highly realistic synthetic identities that can imitate human appearance, voice, behavior, and online presence with unprecedented accuracy. While these technologies offer substantial benefits across education, healthcare, finance, and digital communication, they simultaneously introduce complex cybersecurity challenges that threaten the integrity of digital identity systems and the foundations of trust in cyberspace.
This study investigates the cybersecurity risks associated with AI-generated digital identities and examines how emerging technologies such as deepfakes, synthetic personas, AI-generated biometric data, and automated social engineering techniques can be exploited for malicious purposes. The research highlights the growing threat posed by identity fraud, phishing campaigns, financial deception, unauthorized access, misinformation operations, and attacks targeting biometric authentication mechanisms.
Using a conceptual and analytical research approach, this paper identifies the primary threat vectors associated with synthetic identities and evaluates the limitations of conventional identity verification systems in detecting increasingly sophisticated AI-generated content. Furthermore, the study proposes a trust-aware verification framework that combines multi-factor authentication, behavioral analytics, AI-assisted deepfake detection, and continuous risk assessment to strengthen digital identity protection.
The findings suggest that the rapid evolution of generative AI requires a corresponding transformation in cybersecurity strategies, regulatory policies, and digital trust models. Organizations, governments, and technology providers must adopt adaptive verification mechanisms capable of addressing emerging identity-related threats in an increasingly AI-driven environment. The proposed framework contributes to ongoing discussions on digital trust and cybersecurity resilience while offering practical insights for securing future digital identity ecosystems.
Keywords: Generative Artificial Intelligence, Cybersecurity, Synthetic Identity Fraud, Deepfake Detection, Digital Trust, Identity Verification

ÉVALUATION DE L'EFFICACITÉ ET DE LA SÉCURITÉ DES INHIBITEURS DU COTRANSPORTEUR SODIUM-GLUCOSE DE TYPE 2 (ISGLT2) DANS LA PRISE EN CHARGE DU SYNDROME MÉTABOLIQUE CHEZ LES PATIENTS ALGÉRIENS.

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Abstract

Metabolic syndrome is a major public health concern due to the coexistence of multiple metabolic and cardiovascular risk factors. Sodium–glucose cotransporter 2 inhibitors (SGLT2 inhibitors), particularly dapagliflozin, have emerged as an important therapeutic class in the management of patients with type 2 diabetes mellitus and associated cardiometabolic risk factors.

This study aimed to evaluate the effectiveness and safety of SGLT2 inhibitors in the management of metabolic syndrome among Algerian patients. A multicentre, observational, comparative, cross-sectional study was conducted among patients with type 2 diabetes mellitus and metabolic syndrome, categorized according to their antidiabetic treatment. Clinical and biochemical parameters included anthropometric characteristics, blood pressure, and markers of glycaemic control and insulin resistance. The comparative analysis was designed to characterize differences observed between treatment groups and to assess the metabolic profile associated with dapagliflozin use, either as monotherapy or in combination with metformin. Safety assessment was based primarily on available biochemical parameters and the identification of clinically relevant variations.

This study provides additional insight into the role of SGLT2 inhibitors in the management of metabolic syndrome in the Algerian context and may contribute to a better understanding of their potential metabolic benefits and safety profile in routine clinical practice.

Keywords: SGLT2 inhibitors; l'efficacité; Metabolic syndrome; Type 2 diabetes mellitus; Algerian patients.

THE IMPACT OF ARTIFICIAL INTELLIGENCE TECHNIQUES ON CYBERSECURITY THREAT DETECTION AND RESPONSE MECHANISMS

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Abstract
The escalating scale, speed, and sophistication of contemporary cyberattacks have exposed the structural limitations of traditional, rule-based and signature-dependent security architectures, which are largely reactive and often fail to identify zero-day exploits, polymorphic malware, and adaptive adversarial intrusion strategies. This study examines the extent to which artificial intelligence (AI) techniques, including machine learning, deep learning, and natural language processing, are transforming cybersecurity threat detection and incident response mechanisms. Employing a conceptual and comparative review methodology, the study synthesizes recent literature on supervised and unsupervised learning models, deep neural network-based anomaly detection, behavioral analytics, and AI-driven security orchestration, automation, and response (SOAR) platforms, evaluating their performance against conventional detection approaches in terms of accuracy, false-positive rates, and response latency. The findings suggest that AI-enabled systems markedly enhance the capacity to identify previously unseen and evolving threats, shorten mean time to detection and containment, support predictive threat intelligence, and automate the triage and prioritization of security alerts. Nevertheless, the analysis also identifies persistent challenges, including susceptibility to adversarial manipulation of learning models, dependence on the quality and representativeness of training data, limited interpretability of complex models, substantial computational overhead, and a shortage of specialized workforce skills. The study concludes that the integration of AI into cybersecurity operations constitutes a meaningful shift from reactive to proactive and adaptive defense postures, yet its effective and trustworthy deployment requires continued human oversight, sound data governance, and further research into explainable and adversarially robust AI architectures.
Keywords: Artificial Intelligence, Cybersecurity, Threat Detection, Machine Learning, Incident Response

SACRAL HIATUS: A STUDY OF ITS ANATOMICAL VARIATIONS IN DRY SACRA

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Abstract

Objective: The purpose of the study was found out the anatomical variation in the sacral hiatus which is the sacral canal caudal opening. Its clinical significance is due to the fact that caudal epidural anesthesia is administered through the sacral hiatus and a knowledge of its anomalies is paramount to the success of epidural block. Materials and Method: This study was of three-month duration from September 2019 to December 2019 and was carried out at Khyber Medical College, Peshawar.48 dry sacra from the Anatomy department of Khyber Medical College were studied and the shape of their sacral hiatus was observed along with the level of its apex and base. Results: A total of 48 dry sacra were studied. The sacral hiatus shape was observed which revealed that it was inverted U shaped in 21 (43.8%) cases, inverted V shaped in 14 (29.2%) cases, irregular in 7 (14.5%) cases, M shaped in 4 (8.3%) cases and dumb bell shaped in 2 (4.2%) cases. In majority of the cases the apex was against the fourth sacral vertebrae and the base at the level of fifth sacral vertebrae. Conclusion: Anatomical variation does exist in the shape and size of sacral hiatus and a knowledge of variation in the shape, size, level of the apex and base of sacral hiatus is of importance to the clinicians as epidural anesthesia for therapeutic and diagnostic purposes is administered through the sacral hiatus.

Keywords: Sacral hiatus, Anesthesia, Epidural block

PROCESS DOCUMENTATION OF ETHNOVETERINARY MEDICINE USED AS DIARRHOEA REMEDY IN RUMINANT FARMING IN GUINEA AND RAINFOREST AGROECOLOGICAL ZONES OF NIGERIA

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Abstract
Information on traditional healing methods are rarely divulged by local practitioners to outsiders and, even to some family relations, in addition to rapid changes in the environment, socioeconomic conditions, and technologies which had negative impact preservation of these knowledge. *Therefore, this concern necessitated the need for* process documentation of ethnoveterinary medicine used as diarrhoea remedy in ruminant farming in guinea and rainforest agroecological zones of Nigeria. *A five-stage sampling procedure was used to select 120 respondents. Focus group discussion, Indepth interview with key informant and Interview guide were used to collect the data in eight (8) locations across Nigeria. The result showed that* 70.8% of the respondents reared cattle, 87.5% of them reared sheep while 82.5% reared goat. The result on types of management system used, revealed that most (87.5%) of them practised the semi-intensive system while 40.8% practised the extensive system of rearing ruminant animals. Majority (82.6%) of them indicated family labour as their source of labour while 15.0% of them engaged the services of farm labourers. Furthermore, most (72.5%) of them financed their livestock enterprise using their personal savings while only 4.2% of them secured bank loans for their enterprises. Also, *seven processes of ethnoveterinary practices were documented in Guinea savannah agroecological zone indicating use of Mahogany, Baobab, grass and these included while eight processes were documented in Guinea savannah. Therefore, it is recommended that* Information on process documentation of ethnoveterianry medicine on diarhea in ruminant animals in Nigeria should be transcribed into the farmers' languages across the geographical locations and made available for public use across all the agro-ecological zones in Nigeria by the custodians of EvM information.
Keywords: Ethnoveterinary medicine, process documentation remedy, diarrhoea

INTRODUCTION

Information on ethnoveterinary medicine is usually restricted to older people (Sanhokwe *et al.,* 2016). It has been reported that most ruminant producers inherited this indigenous knowledge of animal healthcare from their forefathers and ethnoveterinary practitioners (Bhat et al., 2012). Similarly, Yigezu *et al.* (2014) reported that information on ethnoveterinary practices are mainly obtained from the aggregated memories of the limited number of ethnoveterinary practitioners living in a particular community.

The essence of documentation of ethnoverinary medicine, as well as it digitalisation, is to ensure that valuable medicinal plant knowledge usage in healthcare management of livestock animals are being preserved permanently. Also, effects of climate change and over-exploitation of land use threaten the availability of EvM materials and cause the disappearance of some of these EvM materials derived from medicinal plants, hence, there is the need for proper process documentation which entails the utilisation of local knowledge to remediate prevalent of animal health problems (Adeniran *et al.,* 2020).

Nevertheless, some of the information on the local remedy used for animal healthcare has not been adequately documented. Indigenous knowledge, based on ethnoveterinary medicine, when properly documented, serves as measures of validating and conserving local resources so as to guide against the indiscrimate use of natural remedies thereby making the process to be sustainable (Ali-Shtayeh, 2016). Process documentation of ethnoveterinary knowledge needs to be disseminated to people in order to

promote the sharing of ideas and information on the available local remedies from medicinal plants and adoption of various conservative measures (Khan *et al*., 2019). Due to this, there is not a sufficient collection of ethnoveterinary knowledge for use now or in the future (Fullas, 2010). Rapid changes in the environment, socioeconomic conditions, and technologies have also had a negative impact on this situation (Tabuti *et al.*, 2003).

Documentation of indigenous knowledge, including ethnoveterinary knowledge, help to preserve some of these knowledge that are in the custody of individuals, families and entire communities from being lost due to people's belief in the secrecy of this heritage. Information on traditional healing methods are rarely divulged by local practitioners to outsiders and, even to some family relations, particularly female children, to guide against the transfer of such knowledge to adjoined families after marriage (Tabuti and Damme, 2012).

Sori, Bekana, Adunga, and Kelbesa (2004) noted that knowledge on ethnoveterinary medicine has not been adequately recorded inspite of the efforts to validate and document ethnoveterinary medicine by researchers in many parts of the nations of the world. To preserve and conserve ethnoveterinary knowledge and sustainably manage ruminant animal diseases, prompt actions need to be carried out to document ethnoveterinary medicine practices. Uwagie-Ero *et al*. (2017) opined that it is important to guide against the loss of ethnoveterinary knowledge by ensuring the sustainable use and conservation practices among farmers. This can be achieved when local remedies for animal healthcare are adequately documented.

Anyaoku *et al*. (2015) posited that local knowledge systems, especially indigenous health knowledge practices in African communities, is gradually moving towards extinction based on the general observation. This can be attributed to the effects of colonisation on Africans which has brought negative impacts, as well as mental colonisation, as marked by their having acutely unfavourable disposition to African things, including local knowledge. Social changes have contributed to the increased degradation recorded in ethnoveterinary knowledge, coupled with the inadequacies in process of documentation of information on natural remedies (Lenka *et al.*, 2018). Adeniran *et al*. (2020) opined that the permanent preservation of local knowledge useful in the management of various animal diseases can be achieved through the documentation and digitalisation of this delicate indigenous knowledge for both present and future use.

METHODOLOGY

The study area is Nigeria. It is in the tropics of West Africa between latitude 4º 14' north and between longitude 2º 2' and 14º 30' east. The land mass of Nigeria is estimated to be 923,768 square km². About 35% of this land mass is left uncultivated, 15% going toward pastures, 10% going toward forest reserves, and 10% going toward settlement while the remaining 30% being arable. Out of total surface area of 91.07 million hectares, it is estimated that 57% is used for pastures and crops and while the other 43% is dedicated to other uses such as forests and water features (Cleaver and Shreiber, 1994). Nigeria is divided into six major ecological zones. These include sahel, sudan savannah, guinea savannah, derived savannah, rainforest and mangrove swamp (Bala, 2010).

The economy of both northern and southern regions are primarily agricultural, with farming as the primary employment for men and women who also process and trade food. Crop farming is predominant in the southern region of the country while ruminant livestock farming is common in the northern region of the country which is largely reared in rural areas with the main purpose to serve as emergency financial resources for the ruminant farmers.

Sampling Procedure and Sample Size

A five-stage sampling procedure was used to select the respondents for this study. Table 3.1 presented the distribution of the study's sampling procedure and sample size.

First stage: This involved the random sampling of 35% of the agro-ecological zones (guinea savannah and rainforest) from all the six zones. These zones include rainforest, mangrove swamp, derived savannah, guinea savannah, sudan savannah and sahel savannah. Second stage: This entailed the random sampling of 30% of states from the selected agro-ecological zones. Out of the six states covered by guinea savannah, Niger and Kaduna were randomly selected while Ogun and Osun were selected from the six states in the rainforest zone. Third stage: This stage involved 10% random selection of Local Government Area (LGAs) from each state selected.

Fourth stage: This involved the selection of two villages in each state to give total of eight villages selected for this study. Fifth stage: At this last stage, i5 respondents were selected in two villages selected in each state to give the 120 respondents selected for this study (60 in rainforest and 60 in guinea savannah).

Both quantitative and qualitative methods were used for data collection in this study. The interview schedule and discussion guide were used as an instrument for quantitative and qualitative data collection. The guide comprises Focus Group Discussion (FGD) and indept Key Informant Interview (KII).

This variable was measured by documenting the process involved in ethnoverinary practices currently used by the ruminant livestock farmers while conducting field survey of this research work in the study area. Tools such as Key Informant Interview (KII), Focus Group Dicussion (FGD), photographs, observations of users, field diaries and videos were used to capture the processes and to ensure that all the information on ethnoveterinary medicine c urrently practised during the period of collecting this data were covered. The FGD sessions comprised group of ruminant farmers and they were conducted in each selected village. Each FGD session had fifteen group members. Each session of discussion lasted for 30 minutes. Also, the interviews of the key informants, such as group leaders, ethnoveterinary practitioners and local leaders was conducted in each selected village for 20 minutes to gather the information relevant to ethnoveterinary medicine in the study area.

RESULTS AND DISCUSSION

Table 1: Distribution of Respondents by Enterprise Characteristics

Variables	Frequency	Percentage
Types of ruminant reared:		
Cattle	85	70.8
Sheep	105	87.5
Goat	99	82.5
Types of management system:		
Intensive	31	25.8
Semi intensive	105	87.5
Extensive	49	40.8
Sources of labour:		
Self labour	69	57.7
Family labour	99	82.6
Hired labour	18	15.0
Years of experience:		
1-5 years	16	13.3
6-10 years	21	17.5
11-15 years	27	22.5
15-20 years	31	26.0
Above 20 years	25	20.8
Sources of finance	87	72.5
Personal saving		
Bank loan	5	4.2
Cooperative societies	11	9.2
Relatives	27	22.5

**** Multiple response variables**

Distribution of Respondents by Enterprise Characteristics

Results in Table 1 reveal that 70.8% of the respondents reared cattle, 87.5% of them reared sheep while 82.5% reared goat. This showed that most of the respondents reared combination of two or three ruminant livestock animals in the study area. This implies that rearing two or three ruminant animals in a single farm could be a form of risk management among farmers and this may also help them to expand the size of the enterprise. This could be probably because they are closely related in term of management system and other shared characteristics or may be to maximise all the benefits. This corroborates the findings of Sanhokwe *et al*. (2016) and Nyako *et al*. (2016) who reported that farmers owned ruminant animals which included goat, sheep and cattle and that majority of the farmers reared goat for religious or cultural purposes.

Also, the distribution of respondents by the types of management system used, as shown in Table 1, revealed that most (87.5%) of them practised the semi-intensive system while 40.8 percent practised the extensive system of rearing ruminant animals. This suggested that most of the respondents adopted both the semi-intensive and extensive systems of rearing ruminant animals in the study area. This implies that the farmers depended greatly on the available pasture within their environment to feed their animals and suggests that farmers will continue to use the vegetation for feeding their animal unrestrictedly unless there is an intervention on sustainable pasture use in various agro-ecological zones in the country. This finding is in line with that of Adedeji *et al*. (2014) and FAO (2019) who reported that most of the farmers, both small holders and nomadic farmers, adopted the extensive system of rearing their farm animals. UNOWAS's (2018) report re-established that the extensive system of rearing is not only peculiar to Fulani alone but to all other rearers. Umanni, Olafadehan and Arowona (2014) reported that majority of farmers who reared small ruminant animals practised semi-intensive system. On the other hand, Aruwayo *et al*. (2019) disconfirm this finding in their own work where they reported that majority of the ruminant producers practised intensive system of farming and attributed this to the current level of security challenges and activities of animal rustlers in the study area.

Moreso, the result on sources of labour shows that majority (82.6%) of them indicated family labour as their source of labour while 15.0% of them engaged the services of farm labourers. This showed that majority of the respondents rely on family members as their farm labour probably because of the nature of farm task required to be performed during the rearing of the ruminant animals. This suggests that ruminant animal rearing is a family engagement where household members are directly or indirectly involved in the production.

Results in Table 1 shows that 26.0% of the respondents had rearing experience ranging from 15 to 20 years, which represented the highest category, while 13.3% of them had farming experience of 5 years and below. This is an indication that ruminant animal production is an age-long practice where the experience of the practices is required. This showed that farmers with increased years of rearing experience have better knowledge of the expected practices involved in animal production. Considering the use of ethnoveterinary medicine, farmers with more years of experience would be at a vantage point in terms of exposure to and practice of traditional remedies. This suggests that years of ethnoveterinary practice is a function of the number of years farmers have engaged in ruminant production.

The implication is that farmers with increased years of rearing would have better inclination to use local remedies than those with reduced years of rearing experience probably because older people are the custodian of ethnoveterinary knowledge which are transferred to the younger ones from one generation to another. This finding agrees with Yussuf *et al*. (2018) and Olorunyomi *et al*. (2019) who reported that majority of farmers had rearing experience of between 1 and 10 years. A higher number of rearing experiences was obtained in the similar work of Ishaya *et al*. (2018) where they reported that most of the large ruminant farmers had years of experience ranging from 1 to 20 years. Adeniran *et al*. (2020) also found that majority of the ruminant farmers have more than ten years farming experience.

Also, Table 1 revealed that most (72.5%) of them financed their livestock enterprise using their personal savings while only 4.2% of them secured bank loans for their enterprises. This revealed that majority of the respondents in the study area financed their farms through personal savings. This is an indication that most of the ruminant livestock farmers had constraint in sourcing for funds. This is in tandem with the findings of Baidoo, Yusif and Anwar (2016) who reported that most of the farmers had no access to farm credit.

Table 2: Process Documentation of Ethnoveterinary Medicine in ruminant diarrhoea

Disease conditions	Number of treatments documented	
	Guinea savanna zone	Rainforest zone
Diarrhea	7(46.7)	8(53.3)

Percentage in parenthesis

Process Documentation of Ethnoveterinary Practices in Nigeria

This section documented the available ethnoveterinary practices in the guinea savannah and rainforest agro-ecological zones in Nigeria, using the qualitative tools such as Key Informant Interview (KII), Focus Group Discussion (FGD), observations of users, while field diaries, photographs and videos were used to capture the processes and to ensure that all information on the processes were covered. The processes of ethnoveterinary practices documented were categorised into two based on the location. These included those used in the guinea savannah and rain forest ecological zones of Nigeria. Table 1 revealed that 7 EvM processes were documented in Guinea savanna zone while 8 EvM processes were documented in Rainforest zone to give a total number of 17 processes of ethnoveterinary medicine documented in selected agroecological zones in Nigeria.

The findings revealed that 7 major processes of ethnoveterinary practices were documented andmahogany, baobab, guinea corn, millet grains, toto grass and cassava peel were major EVM plant materials documented for the remedy of ruminant diarrhoea in the guinea savannah zone in Nigeria. The result of process documentation further recorded that wormcast of earthworm, dried maize comb, cassava peel, Caolin, Mango, Guava and Pawpaw, palm kernel oil, bitter leaf, pap water and bitter gourd leaves were documented as mostly used remedies for the treatment of diarrhoea disease condition in ruminant animals.

Guinea savannah zone

Diarrhoea

Treatment 1

Step 1: Get 500g of Mahogany bark (Wushi)
Step 2: Dry the bark to remove the moisture content
Step 3: Pound the bark and mix with 30g of salt and 1 litre of water.
Step 4: Give the animal to drink or mix with the feed


Mahogany bark and grinded bark 242X209, 14.2KB

Treatment 2

Step 1: Get 500g of Mahogany tree bark (Wushi tree)
Step 2: Air dry the bark of mahogany tree to remove moisture content
Step 3: Grind the bark and mix with 2 litres of water
Step 4: Give 50 cl of the mixture to animal orally.


Mahogany bark and grinded bark- 242X209, 14.2KB

Treatment 3

Step 1: Get 500g of Toto grass (*Ischaemum indicum*)
Step 2: Sundry it to remove the moisture content
Step 3: Grind the Toto grass into powdery form
Step 4: Sieve the grinded grass and add 50g of salt
Step 5: Give 100g to 200g to animal to eat daily.

Treatment 4

Step 1: Get 1 kg fresh Baobab leaves
Step 2: Dry the leaves to remove the moisture content
Step 3: Grind the leaves into powdery form
Step 4: Mix the powder with 2 litres of water
Step 5: Give 50 cl of the mixture to animal orally.



Treatment 5



Step 1: Get the outer peel of cassava up to 1kg
Step 2: Sundry the peel to remove moisture content
Step 3: Pound into powdery form
Step 4**:** Mix with 1kg of feed of animal and give to eat

Treatment 6
Step 1: Get 1 kg of Locust tree bark.
Step 2: Dry the bark to remove moisture content
Step 3: Pound the dried bark into powdery form
Step 4: Mix the powder with 2 litres of water thoroughly
Step 5: Give 50 cl to 100 cl mixture to the animal.





Pap water from Guinea corn 259X194, 4.66KB

Treatment 7
Step 1: Get the pap water from Guinea corn or millet
Step 2: Give pap water to animal to drink and apply to its anus

Rainforest agroecological zone

Diarrhoea

Treatment 1
Step 1: Get Bitter leaves (Ewuro) and Goat weed (Ewe apasa) in the same quantity
Step 2: Squeeze them with water to extract the liquid
Step 3: Give 30 to 50 cl of the extract to the animal orally.



Bitter leaf and Goat weed- 225X225, 8.28KB/ 259X194, 8.71KB

Treatment 2:
Step: Give small quantity of pap water (Omi-Ogi) to animal orally.

Treatment 3:
Step 1: Get extracted palm kernel oil (Adin-dudu)
Step 2: Give spoon drop palm kernel oil (Adin –dudu) to the animal orally



Treatment 4:
Step 1: Get 200g of Bitter gourd leaves (Ewe Ejinrin)
Step 2: Squeeze the leaves with small quantity of water to extract the liquid
Step 3: Give 20 to 30 cl of the extract to animal orally.



Bitter gourd leaves – 265X180, 6.75KB

Treatment 5:
Step 1: Get 200g of Caolin, Mango (500g), Guava (500g) and Pawpaw (500g) leaves
Step 2: Mix them together and give to animal to eat to satisfaction.



Mango leaf, Pawpaw leaf, guava and Caolin – 870X470, 54.1KB/ 275X183, 43.1KB/245X206, 8.17KB/ 259X194, 8.36KB

Treatment 6
Step 1: Get the outer peel of cassava in large quantity
Step 2: Sundry the peel to remove moisture content
Step 3: Feed the animal to satisfaction.

Treatment 7

Step 1: Get dried maize comb of 20 pieces
Step 2: Burn the dried maize comb into ashes
Step 3: Add 1 litre of water to ashes
Step 4: Give up 50cl to affected animal orally.


Maize comb – 299X168, 18.2KB

Treatment 8

Step 1: Get up to 200g of wormcast
Step 2: Airdry the wormcast to remove moisture content
Step 3: Pound the dried wormcast into powdery form
Step 4: Mix the powder with 1 litre of water
Step 5: Shake the mixture thoroughly and give 50cl to


Earthworm cast- 300X168, 18.1KB

CONCLUSION AND RECOMMENDATION

Most of the respondents used plant based ethnoveterinary materials as remedies for diarhea diseases conditions in ruminant farming, thus plant based materials such as leaves , bark and root were documented in process of practising ethnoveterinary medicine in Guinea savannah and rainforest zones. The study concludes that seven EVM practices were available for process documentation while eight processes were documented as remedies for ruminant diarrhoea in rainforest zone as mostly used remedies in the study area.

Based on the findings of the study, the following recommendations are made:

1. Information on process documentation of ethnoveterianry medicine of other diseases conditions affecting ruminant farming should be documented.
2. Information on process documentation of ethnoveterianry medicine on diarhea in ruminant animals in Nigeria should be transcribed into the farmers' languages across the geographical locations and made available for public use across all the agro-ecological zones in Nigeria by the custodians of EvM information.

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INFLUENCE OF NI INCORPORATION ON THE STRUCTURAL, MICROSTRUCTURAL, AND OPTICAL CHARACTERISTICS OF TIN OXIDE THIN FILMS PREPARED BY THE PSP TECHNIQUE

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Abstract

In this study, we employed a pneumatic spray pyrolysis (PSP) technique at a deposition temperature of 450°C to synthesize $Sn_{1-x}Ni_xO_2$ thin films, with the nickel doping concentration varying from 0.0 to 0.10, on glass substrates. The effects of different Ni doping levels on the structural and optical properties of the films were thoroughly investigated. Structural characterization using X-ray diffraction (XRD) confirmed the presence of the rutile phase of SnO_2 in all the thin films. The crystallite sizes were estimated to range between 27 and 47 nm. Optical measurements revealed that the bandgap energy increased from 3.83 eV to 4.01 eV with increasing dopant content, consistent with the Burstein-Moss effect. Additionally, it was observed that both the electrical resistivity and the thickness of the thin films were influenced by the doping levels. The study provides a comprehensive analysis of how Ni doping modifies the intrinsic properties of SnO_2 thin films, highlighting the potential for tuning these materials for specific applications through controlled doping.

Keywords – *Thin films, X–ray diffraction, Optical properties.*

ARTIFICIAL INTELLIGENCE BASED COMPREHENSIVE EXPLORATIONS ON EMERGING TECHNOLOGIES FOR ENERGY SECTOR APPLICATIONS

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Abstract
The emergence of artificial intelligence has opened numerous opportunities in the varieties of the application used by humans in daily life. These applications are from different sectors like healthcare, education, research, transportation, defense, energy, manufacturing, smart cities etc. Among all the sectors, there is significant role in energy which ultimately works as the driving force behind these sectors. The source, consumption and generation of energy for different sectors opens new doors for research to sustain the applicable systems. The demand for energy is increasing exponentially due to utilization of energy in all sectors. The challenges, factors, and sources proving the energy for different sections need to be not only enlisted but also there is need to monitor energy consumption for energy efficient based applications. The rising demand for energy in the above-mentioned sections has direct impact on the future-based applications allied with all these sectors. On the one side, there is exponential rise in the need for energy and on the other has it is challenging to utilize the available energy efficiently. With the emergence of artificial intelligence in diversified sectors, there is strong possibility to address energy-based challenges in the various sectors in a more systematic and efficient manner. Artificial intelligence solution monitors the energy consumptions effectively and provides an optimal solution for energy resources enhancement as well. More incorporation of artificial intelligence enhances the sectors like clean energy, solar system, wind energy, bio energy and biomass, waste management system, grid and power systems, industrial applications, smart cities, automobile systems and many more. Overall, it is very clear to state that the incorporation of artificial intelligence in the above sectors surely improves energy management and sustainability for the ease and growth of society.
Keywords: Artificial Intelligence, internet of things, energy, societal applications

EFFICIENCY AT MAXIMUM POWER OF FINITE TIME CARNOT ENGINE USING ONE COMPONENT PLASMA AS A WORKING MEDIUM IN LOW DISSIPATION REGIME

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Abstract
In this work we investigate the finite-time thermodynamics performances of a Carnot engine operating with a One Component Plasma (OCP) as the working medium under the low dissipation regime. The power output is optimised with respect to time and the expression for the efficiency at maximum power ($\boldsymbol{\eta_{mp}}$) is calculated for the OCP system. Under symmetric dissipation, the efficiency recovers the usual Curzon-Ahlborn Efficiency $\boldsymbol{\eta_{CA} = 1 - \sqrt{\frac{T_c}{T_h}}}$**.** Furthermore, for asymmetric dissipation limits**,** the efficiency at maximum power converges to upper bounds and lower bounds are obtained as $\boldsymbol{\frac{\eta_c}{2-\eta_c}}$ and $\boldsymbol{\frac{\eta_c}{2}}$ respectively.
Keywords: OCP, Finite Time Thermodynamics, Curzon Ahlborn Efficiency.

OPTIMIZATION OF $CSSNI_3$ ABSORBER BANDGAP AND THICKNESS FOR EFFICIENT LEAD-FREE PEROVSKITE SOLAR CELLS

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Abstract
Perovskite solar cells (PSCs) have attracted considerable attention as promising photovoltaic devices because of their high power-conversion potential, low-cost fabrication, and tunable optoelectronic properties. Despite these advantages, the practical application of PSCs remains limited by concerns regarding device performance, operational stability, and the toxicity of lead-based perovskite materials. The quality and physical properties of the absorber layer play a critical role in determining the overall performance of a perovskite solar cell. Choosing a wrong light absorber layer may deteriorate the overall performance of the perovskite -based solar cells despite their unique advantages among the future solar cell generations. Therefore, the selection of an appropriate absorber material, bandgap, and thickness is essential for improving photovoltaic device efficiency. In this study, the optical and structural parameters of lead-free cesium tin iodide ($CsSnI_3$) were investigated for application as the absorber layer in a perovskite solar cell. A device configuration of FTO/TiO_2/$CsSnI_3$/NiO_x/Au was modeled and analyzed using the Solar Cell Capacitance Simulator (SCAPS). The thickness and bandgap of the $CsSnI_3$ absorber layer were systematically varied to determine their influence on the device performance and to identify the most suitable conditions for efficient operation. The simulation results revealed that a $CsSnI_3$ bandgap of 1.5 eV and an absorber-layer thickness of 0.5 µm provide the optimum conditions for the investigated device structure. These parameters are considered favorable for effective light absorption and charge-carrier generation within the absorber layer. The findings demonstrate that optimizing the bandgap and thickness of $CsSnI_3$ is essential for designing efficient lead-free perovskite solar cells. This study also provides useful theoretical guidance for the development and future experimental.
Keywords: absorber layer, band-gap, efficiency, perovskite, thickness, lead-free, solar cells

QUANTUM TELEPORTATION AND ENTANGLEMENT VIA QUANTUM CHANNELS IN BIMETALLIC FE_2CU_2 BASED ON SPIN-1/2 ISING-HEISENBERG CHAIN MODEL

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Abstract
This paper investigates quantum teleportation and entanglement in polymeric bimetallic Fe_2Cu_2 coordination compounds, employing the exactly solvable spin-1/2 Ising-Heisenberg model. Using the transfer-matrix method, we systematically analyze how the anisotropy parameter Δ affects quantum entanglement and teleportation fidelity through Heisenberg spin dimers functioning as quantum channels. Additionally, we analytically calculate the channel concurrence, output state concurrence, formation entanglement, fidelity, and average fidelity as functions of temperature, magnetic field, and anisotropy for different input states, with comprehensive thermomagnetic phase diagrams identifying regions of quantum advantage. Our analysis reveals that Δ governs the fundamental balance between entanglement capacity and magnetic thermal robustness. Consequently, the strongly anisotropic regime is very stable, retaining quantum advantage even at high temperatures and strong magnetic fields due to improved longitudinal correlations, whereas the isotropic case reaches the best teleportation fidelity at low temperatures and weak fields. The results indicate demonstrate that maximally entangled input states consistently outperform partially entangled states. These findings establish that magnetic coordination polymers with tunable anisotropy constitute promising platforms for quantum communication applications, offering a balance between operational fidelity and environmental robustness.

Keywords : Quantum teleportation, Quantum entanglement, Bimetallic Fe_2Cu_2, Ising-Heisenberg model, Fidelity

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ERGOTROPY AND QUANTUM CORRELATİONS İN A DRİVEN TWO-DOUBLE-QUANTUM-DOT QUANTUM BATTERY UNDER 1/F CHARGE NOİSE

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Abstract
We investigate extractable work storage in a capacitively coupled double quantum dot (DQD) quantum battery subjected to experimentally motivated detuning charge noise. The battery is modeled as two interacting charge qubits coupled capacitively through an Ising-type interaction and charged by resonant microwave modulation of the tunnel coupling. Charge fluctuations are described as classical stochastic detuning processes generated from a band-limited 1/f noise spectrum. While the evolution is unitary for each individual noise realization, ensemble averaging leads to an effective loss of coherence and dynamical contrast.
The charging dynamics are characterized through the total ergotropy and its population and coherent contributions, together with the energy-basis populations, a passive-ordering violation indicator, and the Jensen–Shannon coherence of the noise-averaged state. We find that resonant tunnel-coupling modulation predominantly activates an E0↔E· population-transfer channel in the interacting DQD spectrum. The stored extractable work is mainly associated with non-passive population redistribution, whereas coherence develops transiently during the resonant charging process and provides a dynamical signature of the population transfer. Detuning noise suppresses the energy-basis coherence and simultaneously weakens the population-transfer pathway responsible for the dominant population contribution to ergotropy. These results establish a noise-aware framework for semiconductor quantum batteries in which charging performance is quantified through extractable work rather than injected energy alone.
Keywords: Quantum batteries; Double quantum dots; Ergotropy; Quantum coherence; Entanglement; Quantum discord.

GUARANTEED PURSUIT TIME IN A DIFFERENTIAL GAME WITH COORDINATE-WISE GEOMETRIC CONSTRAINTS

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Abstract
This paper investigates a differential game of pursuit involving a single pursuer and a single evader governed by an infinite system of first-order ordinary differential equations in the sequence space l_2. The operational capabilities of both players are restricted by coordinate-wise geometric constraints imposed on their control functions, requiring their action vectors to remain within prescribed resource bounds in l_2 at all times. Unlike standard formulations where pursuit aims at reaching a fixed geometric region or capturing an opponent's physical position, the objective in this framework is to transfer the state trajectory of the infinite system from a given initial state to a prescribed target state within finite time.
Pursuit is considered successful if the pursuer can construct an admissible strategy that guarantees this state transfer regardless of the control strategy selected by the evader. To address this problem, we establish formal mathematical conditions governing the play and analyse the fundamental interaction between the players' geometric resource limits and the system dynamics. We prove a main theorem establishing sufficient conditions for a guaranteed pursuit time and derive an explicit analytical expression for this duration. Furthermore, we construct an explicit, admissible pursuit strategy that actively neutralizes the evader's manoeuvres while steering all components of the system state to the designated target. These results contribute to the theoretical foundations of infinite-dimensional control systems and differential games under geometric control constraints.
Keywords: Guaranteed Pursuit, Coordinate-wise, Geometric constraint.

A QUANTITATIVE REVIEW ON THE PHYSICAL, PHYSIOLOGICAL, AND STATISTICAL PRINCIPLES BEHIND DOWSING IN GROUNDWATER EXPLORATION

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ABSTRACT
Groundwater exploration remains challenging because aquifers occur within heterogeneous geological formations and unsuccessful boreholes can impose substantial costs on rural communities. Dowsing, also known as water divining or water witching, continues to be used as a low-cost means of locating groundwater, despite the availability of established geophysical techniques. This review quantitatively examines the physical, physiological, psychological, and parapsychological principles proposed to explain dowsing. The analysis combines equations from electromagnetism, biomechanics, signal detection theory, and Bayesian statistics with evidence from controlled field experiments. Particular attention is given to proposed magnetic-field effects, electrotelluric currents, water-specific radiation, piezoelectric effects, the ideomotor effect, and extrasensory perception. Quantitative estimates indicate that proposed external physical signals are insufficient to account for the observed movement of dowsing rods: the reported magnetic torque is approximately 3.2×10^{-8} N·m compared with an estimated mechanical requirement of 10^{-5} N·m, while electrotelluric currents of approximately 20 μA are below the cited human perception threshold of 500 μA. No unique electromagnetic radiation from water has been established. In contrast, small involuntary muscular forces of approximately 0.01–0.1 N can produce visible rod displacement, consistent with the ideomotor effect. The review further reports a pooled success rate of 50.3% across 12 double-blind controlled trials comprising 2,940 tests (95% CI: 48.5–52.1%; $p = 0.34$), indicating no statistically demonstrated advantage over chance in the reviewed evidence. The persistence of dowsing belief is discussed in relation to confirmation bias and base-rate neglect. The review concludes that the evidence considered does not establish a physical or parapsychological mechanism for groundwater dowsing and supports the use of validated geophysical approaches for groundwater investigation.
Keywords: Groundwater exploration; Dowsing; Ideomotor effect; Geophysics; Double-blind trials; Confirmation bias.

Introduction
Groundwater is an important component of freshwater supply, particularly in rural regions where surface-water resources may be seasonal or vulnerable to contamination. The reviewed seminar literature describes groundwater as approximately 30% of the world's accessible freshwater reserves and notes its importance for domestic use, livestock, and irrigation. Aquifers are not uniform underground reservoirs; groundwater may occur within fractures, pore spaces, weathered zones, and other geologically controlled structures. Consequently, locating productive groundwater targets without adequate investigation involves uncertainty.

Surface geophysical methods such as electrical resistivity tomography, very-low-frequency electromagnetics, and seismic techniques are used to reduce this uncertainty. However, their equipment, technical requirements, and survey costs can encourage some communities to consider simpler traditional practices. Dowsing involves walking across an area while holding a forked stick, L-shaped rods, or a pendulum and interpreting movement of the instrument as an indication of groundwater. The practice has a long history and has been explained at different times using physical, physiological, psychological, and parapsychological concepts.

The central problem addressed in this review is the absence of a single, quantitatively integrated assessment of the proposed mechanisms of groundwater dowsing. The study therefore examines whether proposed physical signals are measurable at magnitudes capable of moving a dowsing instrument, whether the ideomotor effect can account for rod movement, whether controlled trials demonstrate performance above chance, and how cognitive biases may contribute to the persistence of dowsing belief.

The objective is to synthesize and quantitatively evaluate the principal explanations advanced for dowsing, including magnetic-field gradients, electrotelluric currents, water-specific radiation, piezoelectric effects, the ideomotor effect, sensory leakage, and extrasensory perception. The review also considers controlled field evidence and the statistical interpretation of reported success rates.

Materials and Methods

This study used a structured literature-review approach based on the research seminar from which the present paper was developed. The reviewed material covers literature principally considered for the period 1900–2023, while earlier classical sources were retained where they were relevant to the historical development of dowsing explanations. Evidence was organized into four broad categories: physical mechanisms, physiological and psychological mechanisms, parapsychological claims, and controlled performance studies.

Physical claims were assessed using quantitative relationships from electromagnetism and electrical phenomena. Proposed magnetic effects were examined using the field of a buried dipole and the torque relationship $\tau = m \times B$. Electrotelluric explanations were assessed in relation to streaming-potential relationships and the resulting current that could be available to a human observer. Claims concerning water-specific radiation were examined using radiative power, propagation, and thermal-noise considerations. Piezoelectric explanations were assessed using the relationship $P = d\sigma$ and the resulting electric field under an assumed mechanical stress.

Physiological explanations were examined using a biomechanical representation of rod motion. The net torque on a dowsing rod was treated as the combined effect of muscular and external torques. Physiological tremor and associated angular acceleration were used to estimate the magnitude of muscular torque capable of producing rod movement. Signal-detection concepts were also used to frame the distinction between genuine information and movement arising from noise or unconscious cues.

Evidence for claimed detection ability was assessed from controlled dowsing trials summarized in the seminar. The review reports 12 double-blind controlled trials comprising 2,940 tests. Performance was compared with the 50% chance expectation using confidence intervals and statistical significance. Bayesian reasoning was additionally used to express the evidential strength assigned to a proposed genuine detection mechanism. Cognitive persistence was considered using a simple confirmation-bias model in which successful outcomes receive greater subjective weight than failures.

Findings and Discussion

Physical principles proposed for dowsing

Several physical mechanisms have been proposed to explain how a dowser might detect groundwater. The reviewed evidence considered magnetic-field gradients, electrotelluric currents, water-specific radiation, and piezoelectric effects. Each mechanism requires a physical signal sufficiently large and reliable to influence the instrument or the human observer.

Magnetic-field gradients

The proposed magnetic mechanism assumes that groundwater or mineralized aquifer material produces a local perturbation of the Earth's magnetic field and that a sensitive rod could respond to the resulting gradient. The reviewed calculations give a representative magnetic torque of approximately 3.2×10^{-8} N·m, compared with an estimated mechanical requirement of approximately 10^{-5} N·m for the proposed effect. The magnitude comparison therefore does not provide adequate support for magnetic torque as an explanation of ordinary dowsing-rod movement.

Electrotelluric currents

Groundwater flow can generate electrical potentials through electrochemical and streaming-potential processes. The reviewed calculations estimate currents of approximately 20 μA in the proposed detection scenario, whereas a human perception threshold of about 500 μA is used in the seminar as the

comparison level. The proposed current is therefore approximately 25 times below that cited threshold. This quantitative comparison provides no demonstrated pathway by which such currents could reliably generate the claimed dowsing response.

Water-specific radiation

Dowsing has also been associated with claims that water emits a characteristic radiation or frequency that can be detected by a trained person using a rod or pendulum. The review examines the electromagnetic interpretation of such claims using propagation and thermal-noise considerations. Although a very small theoretical source power can be calculated under assumed conditions, the reviewed literature provides no established detector evidence for a unique water radiation of the type required by the dowsing hypothesis. The proposed mechanism therefore remains unsupported by the evidence considered.

Piezoelectric effects

Stress in quartz-bearing rocks can generate piezoelectric charge. The seminar calculates a theoretical polarization under an assumed stress and obtains a high instantaneous electric field under idealized conditions. However, the review notes that piezoelectric charges associated with steady stress dissipate rapidly, and no controlled evidence is presented linking such transient effects to successful groundwater dowsing. The mechanism therefore does not provide a demonstrated explanation for routine groundwater detection.

Physiological and psychological mechanisms

The ideomotor effect

The ideomotor effect provides a physiological explanation for movement of a dowsing instrument without requiring an external force from groundwater. Expectations or beliefs can produce small, involuntary muscular movements that are amplified by the mechanical sensitivity of a handheld rod. The reviewed biomechanical calculation uses a physiological tremor amplitude of approximately 0.01 rad at about 8–12 Hz. At 10 Hz, the corresponding angular acceleration is approximately 39.5 rad/s²; with a representative rod moment of inertia of 10^{-4} kg·m², the resulting muscular torque is approximately 3.95×10^{-3} N·m. The seminar further reports that unconscious forces in the range 0.01–0.1 N can produce visibly detectable rod displacement. This mechanism can therefore account for rod movement without invoking a groundwater-generated force.

Sensory leakage and unconscious cues

Another possible source of apparent success is the use of environmental information that is not consciously recognized by the dowser. Signal-detection theory distinguishes a genuine signal from background variability using the sensitivity index d′, with $d' = 0$ representing chance-level discrimination. The reviewed material reports a very small estimated effect, approximately $d' = 0.06 \pm 0.08$, and no statistically meaningful evidence that dowsers consistently obtain information beyond chance under controlled conditions.

Parapsychological claims and controlled trials

Extrasensory perception

Some explanations attribute dowsing success to extrasensory perception or another non-material detection mechanism. The seminar evaluates such claims using Bayesian reasoning, in which the posterior probability of a hypothesis depends on its prior probability and the likelihood of the observed evidence. The reviewed analysis does not identify evidence sufficient to establish a parapsychological mechanism for groundwater detection.

Controlled performance

The reviewed evidence includes 12 double-blind controlled trials involving 2,940 individual tests. The accepted abstract and the principal results section report a pooled success rate of 50.3%, with a 95% confidence interval of 48.5–52.1% and $p = 0.34$. This result is close to the 50% chance expectation and does not provide statistically significant evidence of above-chance performance in the reviewed dataset.

Table 1. Summary of quantitative findings reported in the review

Principle/Claim	Calculated value	Comparison	Interpretation
Magnetic torque	3.2×10^{-8} N·m	$\approx 10^{-5}$ N·m required	Insufficient magnitude
Electrotelluric current	20 μA	500 μA cited threshold	≈25× below
Water radiation	Not detected	Theoretical detection level discussed	No established emission
Ideomotor force	0.01–0.1 N	Visibly detectable movement	Mechanically sufficient
Pooled dowsing success	50.3%	50% chance	Not significant; p = 0.34
Bayesian posterior	2×10^{-215}	High posterior required	Effectively negligible

Bayesian interpretation

The seminar reports a Bayesian posterior probability of approximately 2×10^{-215} for a genuine underlying principle when the reviewed evidence is considered under its stated assumptions. This value is presented as effectively negligible. Bayesian interpretation is particularly useful here because it distinguishes a failure to demonstrate an effect from the stronger claim that the observed evidence strongly supports an alternative explanation.

Cognitive biases and persistence of belief

Negative experimental evidence does not necessarily eliminate a belief when successes and failures are remembered or interpreted asymmetrically. The seminar uses a simple confirmation-bias model in which successful outcomes receive a weight greater than failures. With a success-weighting factor of w = 3, ten remembered successes and ten remembered failures yield a subjective probability of 31/42, or approximately 0.74, despite equal objective frequencies. The example illustrates how selective memory can maintain confidence in a practice whose measured performance is close to chance.

Base-rate effects provide a second source of apparent success. If a location has a high natural probability of producing some groundwater, a method can appear successful even when it contributes little information beyond the underlying base rate. Consequently, dowsing claims should be assessed against appropriate controls and local groundwater probabilities rather than against isolated successful wells.

Integrated discussion

Taken together, the reviewed evidence places the proposed mechanisms into two contrasting groups. The physical hypotheses require an external signal capable of producing a repeatable response, but the quantitative comparisons reported in the seminar do not establish such a signal at a sufficient magnitude or with sufficient reproducibility. The ideomotor mechanism, by contrast, provides a direct physiological route from expectation to rod movement and does not require an external groundwater signal. Controlled performance results reported in the review are also consistent with chance expectation.

This interpretation does not imply that groundwater cannot influence measurable geophysical properties. Groundwater can affect electrical, hydraulic, and other physical properties of geological formations, and these properties are precisely why established geophysical methods can be useful. The issue examined here is narrower: whether a dowser holding a simple rod can reliably detect groundwater through a specific physical or parapsychological mechanism. The evidence reviewed in the seminar does not establish such a mechanism.

Practical Interpretation of the Evidence

The reviewed evidence does not establish either requirement for ordinary dowsing. The proposed physical signals are described as weak relative to the relevant mechanical or sensory scales, while controlled performance remains close to the chance expectation. The ideomotor effect, in contrast, requires no unknown force. It only requires ordinary human motor activity acting on a mechanically sensitive instrument. This distinction helps explain why a participant can sincerely observe a rod movement while the movement nevertheless fails to provide reliable information about an aquifer.

The physical calculations and behavioral evidence address complementary aspects of this question. The physical analysis asks whether groundwater can generate a signal of sufficient magnitude and suitable coupling to move the instrument. The behavioral analysis asks whether the participant can identify a

concealed target at a rate reliably greater than chance. A convincing groundwater-detection mechanism would require both a plausible information pathway and reproducible performance.

A central implication of the review is that rod movement and groundwater detection must not be treated as equivalent observations. A rod can respond to a small change in hand orientation even when no external target signal is present. The scientific question is therefore whether the location at which the rod moves can be predicted from information that is unavailable to the participant. Controlled experiments are important because they separate the subjective experience of movement from objective target identification.

Statistical Interpretation of the Controlled Evidence

Statistical significance and practical significance should also be distinguished. Even a statistically detectable effect may be too small to justify a practical groundwater-siting method if it does not substantially reduce drilling risk. Conversely, a practical method would normally be expected to show a reproducible improvement over random selection. The source seminar reports a minimum detectable effect of approximately 2.6%, and no consistent effect of that scale is identified in the reviewed evidence.

The detailed seminar contains a different pooled value of 48.3% for the same 2,940 trials and reports a two-tailed p-value of 0.066. The numerical discrepancy should be resolved by checking the underlying study counts and calculations before final publication. It is not appropriate to conceal the discrepancy because the full-text manuscript should remain traceable to the source material. The present conference version follows the accepted abstract for the principal headline result and records the detailed-table difference as a limitation.

The pooled controlled result deserves careful interpretation. The accepted abstract reports 50.3% success, a 95% confidence interval from 48.5% to 52.1%, and $p = 0.34$. The confidence interval includes 50%, and the reported p-value does not provide evidence against the chance model at the conventional 0.05 level. More importantly, the observed departure from chance is only a fraction of one percentage point.

Implications for Groundwater Exploration

The review therefore does not frame the issue as a conflict between traditional knowledge and modern technology. Instead, it asks whether a proposed method provides reproducible information. Traditional observations may contain useful environmental knowledge, but when a method is presented as a specific detector of hidden groundwater, its performance should be evaluated by objective prediction and drilling outcomes.

The practical cost of a failed borehole should be considered when comparing exploration approaches. A method that is inexpensive to apply but does not improve site selection may create a false economy if it increases the probability of drilling an unsuccessful well. A low-cost geophysical workflow can sometimes reduce this problem by using simplified surveys, locally calibrated interpretation, and validation against existing boreholes.

Groundwater exploration is a decision problem under uncertainty. Geological mapping, hydrogeological reasoning, surface geophysics, and borehole information each provide different types of evidence. Electrical resistivity methods are particularly useful where contrasts in moisture, lithology, and weathering influence subsurface resistivity. The value of such methods lies not in perfect prediction but in measurable information that can be calibrated against known geological conditions.

Limitations of the Review

The review also does not establish that every environmental inference made by experienced practitioners is random. A person may notice surface indicators of groundwater without being consciously aware of them. Such ordinary information should be distinguished from claims of a unique physical or parapsychological detection mechanism. Future experiments should explicitly test this possibility.

Several internal numerical differences are present in the source. The accepted abstract reports 50.3% pooled success, while the detailed seminar table reports 48.3%. The abstract describes $3.2 \times 10{-}8$ N m as approximately 3,000 times weaker than $10{-}5$ N m, although the direct ratio is approximately 312.5. The seminar also gives another minimum-torque estimate. Electrotelluric values likewise differ between sections. These differences should be checked against the original calculations and publications before the manuscript is used as a definitive quantitative meta-analysis.

This manuscript is derived primarily from the supplied M.Sc. seminar and accepted conference abstract. It is therefore a synthesis of those materials rather than an independently preregistered systematic review. The source selection, numerical assumptions, and reported study summaries are inherited from the supplied documents.

Directions for Future Research

Finally, future work should report null results fully. Scientific progress depends on transparent records of both positive and negative findings. Repeated independent testing under controlled conditions would provide a stronger basis for resolving the remaining questions.

Comparative hydrogeological studies could also test dowsing, random selection, and established geophysical methods at the same sites. Objective outcomes such as borehole yield, lithology, and water-table conditions should be recorded. This would allow the practical value of the competing approaches to be compared without relying on anecdotal success stories.

Physiological measurements could provide an especially useful test of the ideomotor hypothesis. High-resolution video, inertial sensors, or electromyography could determine whether small changes in hand or forearm activity precede rod displacement. If movement occurs in the absence of an external target signal, the experiment would provide direct support for a motor explanation.

Future studies should use preregistered, randomized, double-blind designs with all target assignments concealed from participants and experimenters who interact directly with them. Sample size and statistical analysis should be specified before data collection, and unsuccessful as well as successful predictions should be retained in the final dataset.

Hydrogeological Context and the Problem of Target Definition

Consequently, future dowsing studies should report the geological setting, target definition, drilling depth, final yield, and criteria used to classify success. Without these details, percentages of successful predictions cannot be interpreted consistently across studies.

Hydrogeological heterogeneity creates another difficulty. Two sites separated by a short distance may have different fracture connectivity or weathering thickness. A dowser who identifies a location that happens to be productive may attribute the outcome to the rod response, while an investigator may instead explain it through geological structure. The appropriate way to separate these explanations is prospective testing: the prediction must be recorded before drilling and compared with objectively defined geological and hydraulic outcomes.

This distinction affects the interpretation of both successful and unsuccessful predictions. If the criterion is merely the presence of some water, a large proportion of locations may qualify, especially in shallow groundwater environments. The resulting success rate may therefore be high even when the dowsing procedure contributes little information. A more demanding criterion based on productive yield reduces this problem but also requires more expensive validation.

A further issue in evaluating groundwater dowsing is the definition of what constitutes a groundwater target. Groundwater is not simply an isolated underground body that can be treated as a point source. Productive groundwater may occur in fractures, weathered layers, sedimentary units, alluvial deposits, or combinations of geological structures. The presence of water therefore does not automatically mean that a borehole will provide an economically useful yield. A rigorous test of dowsing must define whether the target is any moisture, a saturated zone, a productive aquifer, or a borehole meeting a specified yield.

Why Blinding Is Central to a Fair Test

The source seminar's emphasis on double-blind trials is therefore methodologically appropriate. The reported pooled performance near chance is more informative than individual anecdotes because the experimental design directly addresses the possibility that expectations and environmental cues produce apparent success.

These principles apply to any proposed detection technology, not only dowsing. A geophysical instrument, a human observer, or a machine-learning algorithm must be evaluated against concealed targets if the objective is to demonstrate predictive information. The value of a blind test is that it measures performance under conditions in which expectation cannot easily substitute for information.

A fair protocol should also prevent selective stopping. If a participant is allowed to stop after a sequence of successful responses, the final record can give a misleading impression of accuracy. The number of

trials should be determined before testing. All completed trials, including apparent failures, should be included in the analysis.

Randomization is equally important. Target and non-target locations should be assigned independently of participant expectations. If targets follow a predictable spatial pattern, a participant may exploit that pattern without detecting groundwater. Randomization prevents the participant from learning the target arrangement and converts the task into a genuine information test.

Blinding is one of the most important methodological features in the scientific evaluation of dowsing. If a participant knows where a target is located, the participant may respond to conscious or unconscious cues. Even an experimenter who knows the target location can unintentionally communicate information through body language, tone, timing, or other subtle behaviors. Double-blind procedures reduce these possibilities.

Movement, Perception, and Interpretation

The distinction between experience and evidence is particularly important in traditional practices. Repeated personal experiences can be persuasive, but they may not contain an appropriate control group. If every successful prediction is remembered while failures are forgotten or explained away, the accumulated memory becomes biased toward success. Controlled records correct for this problem by preserving the complete sequence of predictions and outcomes.

This interpretation does not imply that the participant is pretending. In fact, the subjective sincerity of the experience is compatible with an ideomotor explanation. The important scientific question is whether the movement predicts an independently measured target. A genuine feeling of certainty is not a substitute for objective validation.

When a person expects a rod to respond at a certain location, an involuntary movement can therefore occur without the person intentionally producing it. Once the movement occurs, the participant may interpret it as evidence that the expected target has been detected. This creates a feedback loop: expectation influences movement, movement reinforces expectation, and the strengthened expectation influences later movements.

The psychological experience associated with dowsing deserves separate consideration from the physical movement itself. A participant may feel that the rod suddenly becomes heavy, pulls downward, rotates, or moves toward a particular location. Such experiences can be vivid because human motor control normally operates partly outside conscious awareness. We do not consciously calculate every small adjustment required to maintain posture or grip.

Signal Detection Theory as a Bridge Between Physics and Behavior

Applying signal detection theory to dowsing reinforces the need for controlled trials. A reliable detection mechanism should produce a measurable sensitivity above zero under blinded conditions. The source seminar reports performance close to chance and describes sensitivity as statistically consistent with zero. This is consistent with the conclusion that the observed rod movement does not provide demonstrated information about the hidden target.

This framework is particularly valuable in groundwater exploration because the prior probability of water varies between geological settings. A method that appears successful in a water-rich region may perform poorly when transferred to a drier setting. The evaluation must therefore distinguish true discrimination from favorable base rates.

The sensitivity measure d′ represents the separation between signal and noise distributions in standardized units. When d′ is zero, the participant's responses do not reliably distinguish the two conditions. A participant can still have a strong response bias and say “water” frequently. Such a participant may obtain many hits in a high-base-rate environment but also produce many false alarms.

Signal detection theory provides a useful framework because it separates the existence of a signal from the decision rule used by an observer. In a groundwater-dowsing experiment, a participant may produce many positive responses. The number of positive responses alone does not determine whether the participant can detect the target. What matters is whether the response distribution differs systematically between target and non-target conditions.

The Role of Base Rates in Apparent Success

Base-rate awareness also helps explain why anecdotal evidence can be misleading. In an area where water is common, successful predictions are expected even from a poor method. If only successful wells are discussed, observers may infer a strong causal relationship that is not supported by comparative data. This principle is general. A prediction method cannot be evaluated by its success count alone. It must be compared with an appropriate null model. In groundwater exploration, the null model might be random drilling, geological screening without dowsing, or another agreed baseline depending on the research question.

The seminar provides a simple example in which a region has a 60% water base rate and a dowser claims 70% success. The ten-percentage-point difference may appear impressive, but it must be evaluated statistically and economically. Even when the difference reaches statistical significance in a hypothetical calculation, the practical question remains whether the additional information justifies the cost and whether the result can be reproduced in another population.

Base rates are particularly important when evaluating groundwater claims. If six out of ten randomly selected locations in a region can produce some usable groundwater, a person making broad predictions may achieve apparent success without possessing a special detection ability. A method should therefore be evaluated against the success rate that would occur without the method.

Economic and Decision-Making Considerations

The source seminar recommends low-cost geophysical approaches as an alternative where full surveys are difficult to finance. Such approaches can include simplified electrical resistivity investigations, geological mapping, or locally calibrated workflows. Their suitability depends on terrain and project objectives, but they offer a framework in which measurements can be documented, repeated, and compared with borehole results.

This is one reason why validation against actual drilling outcomes matters. A scientifically credible low-cost method could have substantial value even if its predictive accuracy is not perfect. Conversely, a method that appears inexpensive but does not improve the probability of success may not reduce total project cost.

However, the relevant economic comparison should include the expected cost of failure. Suppose two approaches have different initial costs but also different probabilities of locating a productive borehole. The method with the lower survey cost is not necessarily the method with the lower total expected cost. The cost of drilling, mobilization, casing, pumping equipment, and lost time can dominate the initial investigation cost.

The continued use of a low-cost practice can also be understood in terms of decision economics without treating economic preference as evidence of scientific validity. Dowsing requires little equipment and may be available locally. A community facing the cost of a geophysical survey may prefer a method that appears inexpensive and immediate.

Cultural Persistence and Scientific Testing

This approach respects practitioners while maintaining scientific standards. The purpose of a controlled experiment is not to determine whether a person is sincere. It is to determine whether the proposed method predicts the target at a rate that differs reliably from an appropriate null expectation.

Scientific testing is useful because it creates a common standard that does not depend on the reputation of a practitioner or the vividness of an individual experience. A respected dowser and an inexperienced participant can be compared under the same concealed-target conditions. If a skill is genuine and reproducible, it should remain observable when expectation and target information are controlled.

The persistence of dowsing may result from several interacting factors. The practice is inexpensive, easy to perform, visually compelling, and compatible with personal experience. Rod movement provides immediate feedback, while successful wells can create memorable confirmation. In communities where dowsing is transmitted through trusted social networks, these experiences may reinforce one another.

Dowsing has a long cultural history, and scientific evaluation does not require dismissing the cultural significance of the practice. The scientific question is narrower: whether the claimed detection mechanism provides reproducible information about groundwater. A cultural practice can remain meaningful even when a particular physical explanation is not supported.

Integrated Model of Dowsing

The integrated interpretation is therefore consistent with the main conclusion of the supplied seminar: the observed phenomenon of rod movement can be explained through established psychophysiological and behavioral processes, while the additional claim that the rod detects hidden groundwater has not been demonstrated quantitatively.

The model also explains why controlled experiments are essential. Blinding reduces the information available to the participant, randomization prevents predictable target patterns, and complete recording prevents selective memory from determining the final success rate. If performance then remains close to chance, the proposed special detection mechanism lacks empirical support.

This model does not require every apparent success to be caused by the same factor. Some predictions may result from ordinary environmental clues; some may coincide with water by chance; and some rod movements may occur through the ideomotor effect without any useful information. The common feature is that none of these processes requires an unknown groundwater-detection force.

The evidence can be summarized in an integrated model with four stages. First, a person enters an environment containing geological and surface information. Second, prior expectations and environmental observations influence attention and anticipation. Third, small involuntary motor changes can occur as the participant holds a mechanically responsive rod. Fourth, the movement is interpreted as evidence of groundwater and becomes part of the participant's future expectations.

Historical Development of Dowsing Claims

The historical dimension is therefore valuable but should not be confused with empirical validation. Longevity of a practice can demonstrate cultural usefulness, accessibility, or social transmission, but it does not by itself establish the physical mechanism claimed for the practice.

Modern scientific testing changes the question from “Can a dowser find water?” to “Does the dowsing procedure increase the probability of finding water relative to a defined baseline?” This formulation allows dowsing to be evaluated using the same principles applied to any proposed detection method. It also avoids making the conclusion depend on the reputation of a particular practitioner.

The historical use of dowsing also demonstrates why anecdotal evidence can remain influential. If a community repeatedly uses a method and occasionally obtains a productive well, the successful cases provide immediate and memorable reinforcement. However, the relevant comparison is what would have happened at the same sites if the method had not been used. Without that counterfactual comparison, it is difficult to determine whether success was caused by the method, by ordinary geological judgment, or by the background probability of groundwater.

Historically, explanations have often changed when older concepts became less persuasive. A rod movement might first be attributed to a special property of the material of the rod, later to magnetic effects, then to electrical effects, radiation, or other forms of energy. This evolution illustrates an important feature of scientific evaluation: a proposed mechanism must make quantitative predictions that can be tested independently of the observation it is intended to explain.

Dowsing has been described in many cultural settings as a practical method for locating water, minerals, or other hidden materials. The historical persistence of the practice is relevant because it demonstrates that the question is not simply a recent disagreement between modern geophysics and a newly proposed technique. Instead, dowsing has evolved through a mixture of traditional knowledge, local experience, personal testimony, and changing explanations for why a rod moves.

Geological Sources of Groundwater Signals

The appropriate question is consequently one of coupling and information transfer. A proposed mechanism must identify the source, propagation pathway, detector, response threshold, and expected spatial relationship with the aquifer. The reviewed dowsing hypotheses do not establish this complete chain.

This distinction is particularly important because groundwater itself may produce measurable geophysical effects without those effects being perceptible to a person. A scientific instrument can integrate a weak signal over time, amplify it electronically, reject noise, and apply a calibrated interpretation procedure. Human perception does not automatically possess the same sensitivity or specificity. Therefore, the fact that groundwater can influence a measurable geophysical property does not establish that a person holding a rod can detect the influence directly.

Dowsing claims generally begin with the observation that the rod moves in particular places. The missing link is a demonstrated physical pathway that connects the geological condition to the rod through the human observer. The physical mechanisms reviewed in the seminar attempt to supply this link through magnetic, electrical, radiative, or piezoelectric processes. The quantitative analysis finds that these proposed effects do not provide a demonstrated signal of adequate magnitude or a validated human detection pathway.

A proposed detection method must therefore explain how information about these geological properties reaches the observer. Electrical resistivity methods can respond to contrasts in electrical properties. Seismic methods can respond to contrasts in elastic properties. Electromagnetic methods can respond to conductivity and related subsurface characteristics. These techniques have instruments that measure defined physical quantities and models that connect observations to geological interpretations.

Groundwater occurrence is controlled by geological properties rather than by water acting as a uniform underground object. In crystalline rocks, fractures and weathered zones can provide storage and flow pathways. In sedimentary environments, porosity and permeability can vary between layers. In alluvial systems, grain size and depositional architecture influence hydraulic conductivity. These differences mean that groundwater exploration is fundamentally a problem of interpreting geological heterogeneity.

Quantitative Requirements for a Detection Mechanism

The quantitative framework therefore integrates physics and statistics. Physics asks whether a mechanism can produce the response. Statistics asks whether the response predicts the target. Neither component is sufficient alone. A physically plausible effect that does not improve prediction is not an effective detection method, while a statistical effect without a credible mechanism requires independent replication and further investigation.

A further requirement is reproducibility. A mechanism that occasionally produces a response but does not do so under repeated controlled conditions cannot serve as a reliable detection technology. This is especially important for groundwater because drilling decisions are discrete and costly. A method must provide information consistently enough to improve the decision relative to an appropriate baseline.

The quantitative approach is valuable because it prevents an explanation from becoming unfalsifiable. If a proposed signal is said to be “very weak,” the relevant question becomes how weak and how that magnitude compares with the detector threshold. If a proposed effect is transient, the question becomes how long it persists and whether it coincides with the target-selection event. If a signal is said to travel through the ground, its attenuation and propagation characteristics should be specified.

The source seminar addresses several of these requirements. For the magnetic hypothesis, the torque calculation tests whether the field can mechanically rotate the rod. For the electrotelluric hypothesis, the current calculation tests whether a natural electrical signal could reach a level relevant to human perception. For the radiation hypothesis, the absence of an independently detected emission tests whether the proposed signal has been established instrumentally. For the piezoelectric hypothesis, the temporal behavior of the effect is considered.

A useful scientific model should generate numerical predictions. For groundwater dowsing, a minimum set of requirements can be stated. First, a proposed signal must originate from the groundwater or a feature reliably associated with productive groundwater. Second, the signal must propagate through the geological material. Third, the signal must interact with the human body or the dowsing instrument. Fourth, the resulting response must exceed the relevant detection threshold. Finally, the response must contain information that distinguishes target from non-target locations.

Comparison with Established Geophysical Exploration

The central difference is therefore methodological. Established geophysics treats uncertainty as something to be measured and managed. Dowsing claims, when presented without controlled validation, can treat subjective confidence as evidence. The review supports the former approach because it allows predictions to be independently tested.

For rural groundwater development, a practical strategy can involve progressively more detailed investigation. Existing geological and hydrogeological information can be used first, followed by an appropriate low-cost geophysical survey where necessary. Borehole drilling then provides direct validation. Such a workflow makes uncertainty visible and creates a record that can be used to improve future site selection.

The comparison should nevertheless be made fairly. Geophysical methods can be expensive and can fail when geological conditions are complex, data quality is poor, or interpretation is ambiguous. Their use requires expertise. These limitations are reasons to improve geophysical practice and develop affordable workflows, not reasons to assume that an unvalidated alternative is automatically more reliable.

Dowsing differs in that the primary measurement is often a human response to rod movement. The response can be difficult to record independently, and the mechanism linking it to the subsurface is disputed. A controlled test can determine whether the response predicts hidden targets, but the source evidence summarized in this paper does not show a consistent improvement over chance.

The practical advantage of these approaches is not that they provide certainty. Instead, their measurements can be repeated, calibrated, filtered, modeled, and compared with borehole information. If an interpretation is wrong, the discrepancy can be investigated by examining the data and the assumptions. This creates a cumulative process of technical improvement.

Established geophysical methods provide a useful reference point for interpreting the dowsing evidence. Electrical resistivity methods measure voltage and current relationships and infer subsurface resistivity. Electrical resistivity tomography can generate two-dimensional or three-dimensional representations of resistivity variation. Very-low-frequency electromagnetic methods respond to electromagnetic properties, while seismic techniques use the propagation of elastic waves. Each method has limitations, but each also has an explicit measurement principle.

Experimental Design for a Definitive Dowsing Study

A particularly useful design would compare three approaches: dowsing, random selection, and an established geophysical method. All three would operate on the same set of geological environments. The outcome could be borehole productivity and cost per successful borehole. Such a study would answer both the scientific and practical questions: whether dowsing contains predictive information and whether that information is useful enough to change groundwater-development decisions.

Statistical analysis should be specified in advance. A binomial model can test whether the observed success proportion differs from chance, while sensitivity and specificity can be reported when target and non-target classes are defined. Confidence intervals should accompany point estimates. If multiple hypotheses are tested, the analysis should account for multiple comparisons or clearly label exploratory results.

The fourth stage would record all predictions prospectively. Each prediction should include location, date, target classification, and the dowser's stated confidence if confidence is part of the hypothesis. The record should be time-stamped or otherwise protected against retrospective alteration. Drilling outcomes should then be recorded using the predefined success criterion.

The third stage would standardize the dowsing procedure. The participant should specify how the rod response is recorded, what constitutes a positive prediction, and how uncertain responses are handled. Multiple participants can be tested independently to distinguish individual performance from group-level effects.

The second stage would generate candidate locations using independent hydrogeological information and randomization. Target and control locations should then be concealed from the dowser. Ideally, the person who interacts with the dowser should also be blind to target status. This prevents subtle communication from becoming an uncontrolled information channel.

A rigorous future experiment could be designed as a prospective groundwater-location study. The first stage would define the target. For example, a target might be a location within a specified area that has a borehole yield above a predetermined threshold. The threshold should be defined before testing rather than selected after results are known.

Data Quality, Reproducibility, and Reporting

A transparent evidence base would make it possible to update the conclusions as new experiments are conducted. If a reproducible above-chance effect were demonstrated under stringent conditions, the scientific position should change accordingly. Conversely, repeated null results would strengthen the conclusion that apparent dowsing success arises from ordinary physical, psychological, or statistical processes.

Publication bias is another concern. If unsuccessful dowsing tests are less likely to be reported, the published literature can overestimate performance. Future studies should therefore be encouraged to

report null results and failed replications. Conference proceedings and institutional reports may contain relevant information, but their methodological quality should be assessed rather than assumed.

Reproducibility also requires consistent terminology. "Success," "water," "groundwater," "productive borehole," and "aquifer" should not be used interchangeably unless they have been operationally defined. A study that counts any moisture as success is testing a different hypothesis from one that requires a productive well.

Raw or study-level data are particularly valuable because they allow independent researchers to reproduce pooled calculations. If a reported percentage cannot be traced back to the number of successful and unsuccessful trials, confidence in the pooled result is reduced. The same principle applies to physical calculations: assumptions, units, parameter values, and intermediate steps should be shown clearly enough for another researcher to reproduce the estimate.

The reliability of a quantitative review depends on the transparency of the underlying data. In the present source material, numerical discrepancies demonstrate why calculations and study-level data should be preserved. A future meta-analysis should provide the number of participants, number of trials, target definition, success count, protocol, blinding status, and statistical method for every included experiment.

Overall Synthesis of the Review

The review consequently supports a clear distinction between cultural practice, subjective experience, and scientific detection technology. Dowsing can be studied respectfully as a human practice while still requiring quantitative evidence when it is proposed as a method for locating groundwater.

For groundwater practice, the conclusion is pragmatic. A borehole location should be supported by evidence that can be independently evaluated. Where geophysical resources are limited, the appropriate response is to develop simpler and cheaper versions of validated methods, improve local geological databases, and strengthen borehole validation. The scientific evaluation of dowsing should continue to use fair tests, but current evidence does not justify replacing established groundwater-investigation procedures with divining rods.

The strongest evidence is therefore not the failure of one proposed physical hypothesis in isolation. It is the convergence of several lines of analysis. The proposed magnetic, electrical, radiative, and piezoelectric mechanisms face quantitative problems; the ideomotor mechanism can account for movement; and the controlled performance data do not show a reproducible advantage over chance. The combined interpretation is more informative than any single calculation.

This hierarchy does not require every dowsing experience to have one identical explanation. Different experiences may involve different combinations of environmental information, expectation, involuntary movement, and chance. What is not demonstrated is an additional groundwater-specific detection mechanism that reliably improves prediction when ordinary information is controlled.

Taken together, the reviewed evidence forms a coherent hierarchy. At the level of physics, the proposed external mechanisms do not provide a demonstrated signal sufficiently coupled to the human-held rod. At the level of physiology, small involuntary movements provide a well-established route by which a rod can move without conscious intention. At the level of behavior, controlled trials summarized in the supplied materials remain close to chance. At the level of psychology, confirmation bias and base-rate neglect provide plausible reasons why belief can persist despite mixed objective outcomes.

Scientific Criteria for Accepting a Groundwater-Detection Claim

These criteria provide a neutral framework for evaluating future dowsing claims. They do not require researchers to assume beforehand that dowsing cannot work. Instead, they specify what evidence would be necessary to demonstrate that it does. If future experiments meet these criteria and produce a reproducible effect, the conclusion of the present review should be reconsidered. Until then, the evidence summarized in the supplied materials does not establish a reliable groundwater-detection mechanism.

Fifth, the mechanism should be open to measurement. If a proposed physical signal is responsible for the response, its magnitude, propagation, and interaction with the detector should be measurable in principle. A mechanism that is defined only by the outcome it is intended to explain cannot be tested independently.

Fourth, the result should be reproducible. A single successful demonstration is insufficient for a general claim about a detection technology. Independent participants, researchers, and locations should be able to obtain comparable results. Reproducibility is particularly important when the proposed mechanism is unusual or lacks an established physical basis.

Third, the experiment should contain an appropriate control or comparison condition. A success rate of 60% has little meaning if 60% of random locations in the same environment also contain usable groundwater. The correct question is whether dowsing improves prediction beyond the baseline available without dowsing.

Second, the prediction should be prospective. The dowser should identify the target before the outcome is known, and the prediction should be recorded in a form that cannot be changed after drilling. Prospective recording prevents hindsight from influencing the evaluation. It also permits unsuccessful predictions to remain part of the evidence.

A scientifically credible claim of groundwater detection should satisfy several criteria simultaneously. First, the target must be defined independently of the claimed detection response. If a location is classified as successful only because the dowser responded there, the test becomes circular. Success should instead be based on an external criterion, such as a predetermined borehole yield or a documented hydrogeological condition.

Relevance to Rural Water Development

The findings of this review therefore have implications beyond the specific debate about dowsing. They support a general principle for groundwater development: methods used to make costly decisions should be evaluated against measurable outcomes and appropriate baselines. This principle allows traditional practices, modern geophysics, and other proposed techniques to be considered within the same evidence framework.

From this perspective, the scientific evaluation of dowsing is part of a larger problem of evidence-based groundwater management. The goal is not simply to determine whether a rod moves. The goal is to improve the probability that scarce resources are invested in locations with defensible hydrogeological evidence. Validated geophysical methods are valuable because their measurements can be documented, compared, and improved. Where those methods are currently inaccessible, developing affordable versions should be a research and development priority.

The review also highlights the importance of communicating uncertainty. Communities should understand that no exploration method guarantees a productive borehole. A responsible investigation should explain the evidence supporting a site, the uncertainty remaining after the survey, and the reasons for the final drilling decision. This is preferable to presenting either dowsing or geophysics as infallible.

Local calibration can further improve the practical usefulness of geophysics. For example, resistivity values measured in one geological environment may have different meanings in another because of differences in lithology, clay content, salinity, moisture, and saturation. Using existing boreholes as calibration points can reduce uncertainty and make interpretations more locally relevant.

The appropriate scientific response is not merely to criticize an inexpensive practice. It is to improve access to validated alternatives. A community may not be able to afford a full geophysical campaign, but simplified surveys, local geological mapping, existing borehole records, and targeted electrical measurements can sometimes provide useful information at lower cost. Capacity building is also important because the value of a geophysical survey depends on correct acquisition and interpretation.

The groundwater question has an important practical dimension because unsuccessful boreholes can affect household finances, community resources, and access to water. In many rural environments, the choice of a drilling location is made with incomplete geological information. The attractiveness of dowsing is partly explained by this uncertainty: it appears to provide a simple decision rule without requiring expensive equipment.

Final Evidence Assessment

Taken together, these findings support the conclusion that the movement of a dowsing rod should not be interpreted as established evidence of a hidden groundwater signal. The ideomotor mechanism provides a coherent explanation for involuntary movement, while cognitive and environmental factors can contribute to apparent success. The appropriate scientific position is therefore open to further testing but does not treat dowsing as a validated groundwater-exploration technology.

The final requirement is practical value. Even if a small statistical effect were eventually demonstrated, its usefulness would depend on whether it reduced unsuccessful drilling enough to justify its use. A method for groundwater exploration must ultimately improve decisions about where to drill. On the evidence reviewed here, that practical advantage has not been demonstrated.

The fourth requirement is reproducibility. A useful detection method should produce comparable results when tested by independent researchers and under different conditions. The supplied evidence does not establish such reproducibility for dowsing. The absence of a demonstrated reproducible effect is especially important when the proposed mechanism is outside established geophysical practice.

The third requirement is behavioral discrimination. A participant must identify target locations more accurately than would be expected from chance and available background information. The accepted conference abstract reports a pooled result of 50.3% with a 95% confidence interval of 48.5–52.1% and $p = 0.34$. This result does not demonstrate an above-chance detection effect. The detailed seminar table contains a different pooled percentage, which is explicitly identified elsewhere in this manuscript as a numerical discrepancy requiring verification.

The second requirement is a plausible information pathway. The physical mechanisms considered in the seminar attempt to provide such a pathway, but the calculated magnetic and electrical effects are reported as too small relative to the relevant thresholds, while the proposed water-specific radiation has not been independently demonstrated. Piezoelectricity is a real physical phenomenon, but the source analysis indicates that the proposed effect is not sustained under the conditions required to explain ordinary groundwater dowsing.

The overall evidence can be assessed by considering whether the proposed dowsing procedure meets the requirements of a reliable detection technology. The first requirement is a defined target. Groundwater occurrence is controlled by geology and hydraulic conditions, and the source material recognizes that not every occurrence of subsurface water represents a productive borehole. This makes objective target definition essential.

Conclusion and Recommendations

This quantitative review examined the principal physical, physiological, psychological, and parapsychological explanations proposed for groundwater dowsing. The reviewed calculations do not establish magnetic, electrotelluric, water-radiation, or piezoelectric effects capable of explaining routine dowsing-rod responses. In contrast, the ideomotor effect provides a quantitatively plausible explanation for rod movement through small involuntary muscular actions. The controlled-trial evidence summarized in the study reports performance close to the 50% chance expectation, with a pooled success rate of 50.3% and no statistically significant advantage.

Based on the evidence reviewed, the following recommendations are made:

• Dowsing should not be treated as the primary technical method for groundwater exploration where validated geophysical investigation is available.

• Groundwater development projects should consider appropriate geophysical surveys before drilling, particularly where drilling costs and failure risks are substantial.

• The ideomotor effect and principles of experimental control should be included in relevant earth-science and public-science education to improve understanding of dowsing responses.

• Further double-blind studies may be conducted across different hydrogeological environments, with transparent reporting of both positive and null results.

• Future studies should compare dowsing, random site selection, and validated geophysical methods under the same hydrogeological conditions and with clearly defined success criteria.

Acknowledgements and Information Note

The author expresses appreciation to Prof. Mohammed Saleh, Department of Physics (Geophysics), Bayero University Kano, for supervision and academic guidance. The work was developed from a research seminar in geophysics submitted to the Department of Physics, Faculty of Physical Science, Bayero University Kano.

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INVESTIGATION OF DYNAMIC EFFECTS OF WIND DRIFT OF ICE FIELDS

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Abstract
Paper presents the results of computer modeling of the drift of ice fields under action of the wind at varying in time velocity, which reflects real stages of the wind: origin, existence and disappearance. Ice fields are modeled in the form of flat plates of varying sizes and thicknesses corresponding to real ice fields observed in the Arctic seas. Differential equation of motion of isolated ice field was used for modelling, which takes into account the inertia of ice field and the attached water mass, the effect of wind on the surface part of ice field and the resistance to the movement of the water mass on submerged part of the ice field. To parameterize the effect of wind and the resistance of water mass, the well-known methods of Aerodynamics and Naval Architecture were used, which are applied to calculate the speed of the ship usually. The simulation results show that due to the inertia of ice fields, the wind-induced drift of ice fields continues after the wind stops, the longer the larger dimensions and thickness of the ice field. The results of the study are of practical interest for the management of ice situation in the water areas of the location of facilities for development of mineral resources of the Arctic seas shelf.
Keywords: Arctic sea, ice field, wind, drift, velocity, distance, wind.
Highlights:
1. Arctic seas are covered with ice cover most of the year and part of them drift under effect of winds and currents.
2. The ice fields can drift without interaction with other ice in the water areas were the ice concentration is not great.
3. The methods of Naval Architect and Aerodynamics were applied to describe the wind drift characteristics of an isolated ice field.
4. Computer modelling revealed the ice field drift continuous after the wind disappearance due to inertia, and the time longer the larger the dimensions and thickness of the ice field.

Introduction

The ice cover of the Arctic seas is in constant motion, and for this reason it has a diverse impact on all types of economic activity, including navigation along the Northern Sea Route and the development of mineral resources of the shelf. Oil-producing platforms and terminals are located on the shelf of the marginal Arctic seas which separated from the main water area of the Arctic Ocean by separate islands and archipelagos.

Therefore, the drift of the ice cover in these seas is not an integral part of the overall drift of the ice mass in the Arctic Ocean, but the exchange of ice from time to time occurs under the influence of local winds and currents (Kan, 1974; Doronin and Heisin, 1975). Therefore, the ice concentration in the adjacent seas is less than in the central Arctic, and the single ice fields have the ability to drift independently under the influence of the local winds affecting the platforms and terminals when drifting ice fields collide with them. The collision of a drifting ice field with an obstacle leads to the breakdown of the ice field and the accumulation of the ice fragments near obstacle, which impedes the functioning of the platforms and the terminals.

The consequences of the collision of drifting ice fields with an obstacle: the size of possible accumulations of the ice fragments, are estimated and presented in the works (Goncharov, 2022; Goncharov, 2023; Goncharov, 2024). The studies in these works were carried out on the basis of the

assumption of the steady drift, that is the movement of an ice field with a constant speed under the impact of causing drift wind that has certain constant velocity. The main outcomes of these studies can be considered as follow: firstly, the identification of the physical cause of the occurrence of the piles with ice fragments near platforms and terminals, namely, collision with drifting ice fields, and, secondly, the relationship between the volume of the ice fragments and the dimensions of the ice fields.

The disadvantage of these studies is the assumption of a time-established drift of the ice fields. This may be realistic for condition of very long time of the wind with unchanged velocity and direction and for low ice concentration, when there are relatively large spaces of the clear water surface in comparison with the size of ice fields.

To solve this problem, it is necessary to describe the drift of the ice field under the action of the wind on upper surface that changes in time and the drift resistance of the water mass on lower surface.

To date, methods have been developed for predicting the wind drift of ice masses on the scale of individual seas and the entire Arctic Ocean (Goncharov and Karpuk, 2026). The application of these methods to relatively small ice fields in coastal water areas is inadequate as it does not allow taking into account local features of wind and currents, as well as the size of isolated ice fields. The problem of describing the drift of isolated ice fields under the influence of the wind was considered in the work (Voitkunsky, 1988), and the Nansen formula for a continuous ice cover was used to estimate the speed of the small ice field drift. The paper (Devnin, 1983) presents the equation of ice field drift under the influence of invariable wind and current. However, due to the uncertainty of the values of the coefficients of resistance for wind and current on the upper and lower surfaces of the ice field, an empirical formula was also used for practical calculations.

The presented study, the drift of the ice field was investigated throughout the entire cycle of wind existence: origination – being – disappearance, and subsequent an ice field drift by inertia, which makes it possible to identify the dynamics of drift: its velocity, duration and distance of acceleration and deceleration of the ice field depending on its dimensions and the characteristics of the wind action.

Preliminary results of study were presented on the Conference IAHR 2026 (Goncharov and Karpuk, 2026). Article presents the formulation of the problem, the mathematical model of the wind drift of the ice field and the results off a computer study of the drift characteristics dependence on the ice field dimensions and the wind characteristics (to a great extent then in (Goncharov and Karpuk, 2026)), which allow to more fully understand the main patterns of wind drift of cover in the Arctic seas.

Materials and Methods

Many nature factors influence on the wind drift of an ice field including dimensions and form of the water area, presence and direction and velocities of currents, the ice concentration, relative positions and interaction of the ice fields, the wind velocity an it direction, and also the ice field thickness variation due to ice freezing and snow fall nonuniformity. All these circumstances complicate the understanding and parametrization of the ice drift process, therefore significant simplification of the process is required for its mathematical description and analysis of its specific features and dependence on the affecting it parameters.

Following assumptions were accepted to develop the mathematical model of the wind drift of an ice field development.

The water area has sufficiently large transverse dimensions and depth that do not affect the characteristics of the ice field drift.

There are no currents in the water area (the water mass is stationary one).

The wind direction is invariable.

There is no interaction of the under-study ice field with other ice fields in the water area.

The shape of the drifting ice field is not considered and characterized by the average thickness, the surface area and the size of the side of a square that has equal area.

There is not hummocking of the ice field under consideration.

The shape of the ice field drift trajectory is not considered therefore the geostrophic effects are not taken into account.

The scheme of the ice field drifting under the wind forcing in the *OXYZ* coordinating system is presented in Figure 1. The wind is directed along the *OX* axis and the ice field drift is also directed along *OX* axis due to absence of the geostrophic effects.

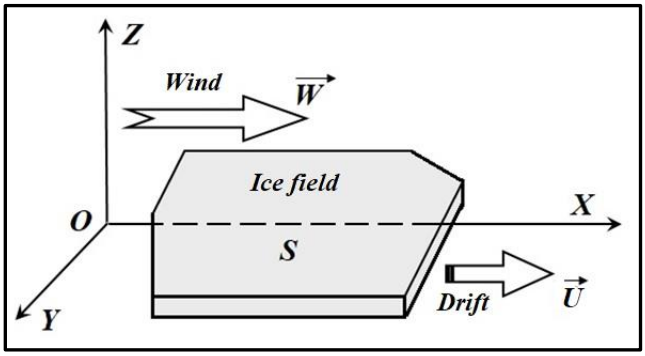


Figure 1. Formulation of the problem of the wind drift of an ice field.

The forces acting on the ice field and their sites of action are shown in Figure. 2. Wind sets in movement (drift) the ice field forcing on its upper surface by the friction force and the velocity head on the above water windward side of the ice field. The resistance to the movement (drift) of the ice field from the water mass consist of the friction on the lower surface of the ice field and the water head on the submerged part of the leeward side of the ice field.

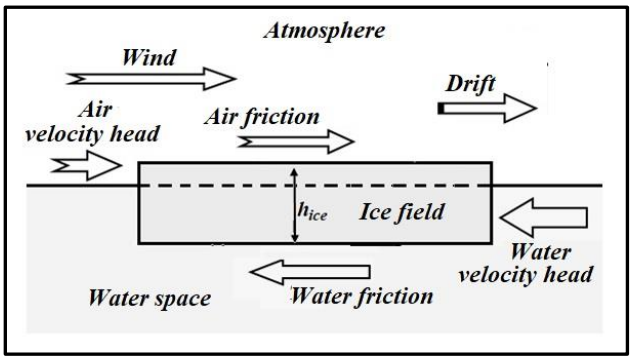


Figure 2. Scheme of the forces acting on a drifting ice field.

The methods of the Naval Architect developed to assess the resistance to the motion of the ship (Voitkunsky, 1988) and the methods of the Aerodynamics to assess the resistance to flow around bodies of various shape (Devnin, 1983) are used to determine the magnitude of the forces and their total effect on the ice field drift.

The equation of ice field drift under the influence of wind, the speed of which varies in time, has the following form

$$\left(M_{if}+m_w\right)\frac{d^2x}{dt^2}=\sum_i F_a^i\left[t,W\left(t\right),U\left(t\right)\right]-\sum_j R_w^j\left[t,U(t)\right]. \quad (1)$$

In this equation, M is the mass of the ice field, m_w is the added water mass, F_a^i is the i -wind-induced force acting on the ice field depending on the wind velocity $W(t)$, R_w^j is the j - resistance force of the water mass to the movement of the ice field depending on the speed of the ice field drift $U(t)$, and x, t are the coordinate of the ice field along OX axis and time.

The initial conditions for the drift equation (1) are as follows

$$t=0 \qquad x=0,\quad \frac{dx}{dt}=0,\quad \frac{d^2x}{dt^2}=0,\quad W(t)=0,\quad U(t)=0. \quad (2)$$

The equation (1) is a nonlinear differential equation of the second degree. It can be converted into an equation of the first degree if we take into account that the variable x is not explicitly present on its right side. Assuming the drift velocity $U\left(t\right)=dx/dt$ as unknown, the equation (1) was transformed into the following form

$$\left(M_{if}+m_w\right)\frac{dU}{dt}=\sum_i F_a^i\left[t,W\left(t\right),U\right]-\sum_j R_w^j\left[t,U\right]. \quad (3)$$

Initial conditions for this equation are as follow

$$t = 0 \qquad U = 0, \quad \frac{dU}{dt} = 0, \quad W(t) = 0. \tag{4}$$

The distance (coordinate x) of the ice field drift as a function of time t is determined as follow

$$x(t) = \int_0^t U(t)\, dt. \tag{5}$$

The integration of equation (3) and calculation of the integral (5) should be performed until the moment when the drift of the ice field caused by the wind will disappear. This moment $t = T_{fin}$ corresponds to some minimally discernible value of the drift velocity $U(T_{fin}) = U_{min}$.

Parameterization of Components of the Ice Field Wind Drift Equation

In real conditions, ice fields have different shapes in plan and varying thickness, which were formed under the influence of conditions of its formation, drift, mutual collisions and other processes. Ice fields of various form oriented during the process of drifting in such way that the yaw moment caused by external random influences is minimal. In addition, there may be separate hummocks and hummock ridges on the ice field, the role of which is not taken into account. In this study, the specific shape of the ice field is not determined, and it is characterized by its surface area S and thickness h_{ice}. For subsequent estimates of the effects of wind and water mass on the ice field, it is customary to use the value of $\sqrt{S}$ as linear dimension. The mass of the ice field under the assumption of the absence of hummocks is determined as follows

$$M_{if} = \gamma_{ice}\, h_{ice}\, S. \tag{6}$$

The attached water mass is estimated by the following formula

$$m_w = k_{11}\, \gamma_w\, h_{ict}^w\, S \tag{7}$$

In these formulas k_{11} - is the coefficient of added water mass, γ_w - the density of the sea water, γ_{ice} - the density of the ice, h_{ice}^w - the thickness of the ice field which is below the sea water level and depends on the densities water and ice and is determined by the following formula

$$h_{ice}^w = \frac{\gamma_{ice}}{\gamma_w} h_{ice}. \tag{8}$$

The value of the attached mass coefficient k_{11} was accepted as attached mass of the parallelepiped with a square base, that is $k_{11} = 1.51$ (Korotkin, 1986). In view of the stated above “effective” mass of the ice field is determined by the following formula

$$M_{wi} = (1 + k_{11})\, \gamma_{ice}\, h_{ice}\, S \tag{9}$$

The frictional force of the wind on the upper surface of the ice field and friction of the water mass on the lower surface are determined by identical formulas

$$F_{fr}^1(t) = \frac{1}{2} \zeta_{fr}^a\, \rho_a \left[W_s(t) - U\right]^2 S, \qquad R_{fr}^1 = \frac{1}{2} \zeta_{fr}^w\, \rho_w U^2 S. \tag{10}$$

In these formulas ρ_a, ρ_w are mass densities of an air and water, $\zeta_{fr}^a, \zeta_{fr}^w$ are the coefficients of the friction resistance for the air on upper surface and the water on lover surface of the ice field. The friction coefficients in this problem correspond to the turbulent mode of the air and water movement in the boundary layers and depend on Reynolds number by following way (Voitkunsky, 1988).

$$\zeta_{fr}^{a} = 0.455\left[\lg\left(\mathrm{Re}_{a}\right)\right]^{-2.58}, \quad \mathrm{Re}_{a} = \left(\frac{W(t) - U(t) + v_0}{\nu_a}\sqrt{S}\right),$$
$$\zeta_{fr}^{w} = 0.455\left[\lg\left(\mathrm{Re}_{w}\right)\right]^{-2.58}, \qquad \mathrm{Re}_{w} = \left(\frac{U(t) + v_0}{\nu_a}\sqrt{S}\right). \tag{11}$$

In these formulas ν_a, ν_w are coefficients of the kinematic viscosity of an air and water, v_0 is velocity of the minimum value that eliminates the singularity at the initial moment ($t = 0$) when there are wind and drift.

The frictional force of the wind on the over-water part of the ice field is determined by the wind velocity relative to drifting ice field and its surface area. The upper surface of the ice field is located relative the water surface at a height of

$$h_{ice}^{a} = \frac{\gamma_w - \gamma_{ice}}{\gamma_w} h_{ice}. \tag{12}$$

Using the well-known expression for the wind velocity profile in the surface layer (Stewart, 2009), the wind velocity at the upper surface of the ice field is determined as follows

$$W_s(t) = W_{10}(t)\left(1 + \frac{\sqrt{c_w}}{\chi_0}\ln\frac{h_{ice}^{a}}{z_{10}}\right). \tag{13}$$

In this formula W_{10} - velocity of wind at altitude z_{10} = 10 м about sea level (as it accepted for oceanography and aerography in the ocean conditions), χ_0 = 0.4 – Karman's constant for turbulent friction), c_w = 1.11·10^{-3} is coefficient of the wind friction on the sea surface at the minimum level of sea waves because covered with drifting ice that .

The velocity head on the above-water part of the windward side of the ice field and the head resistance of the water mass on the underwater part of the leeward side of the ice field are presented as follows

$$F_{hp}^{2}(t) = \frac{1}{2}\zeta_{hp}^{a}\rho_a\left[W_h(t) - U\right]^2 h_{ice}^{a}\sqrt{S}, \qquad R_{hp}^{2}(t) = \frac{1}{2}\zeta_{hp}^{w} r_w U^2 h_{ice}^{w}\sqrt{S}. \tag{14}$$

It can be assumed the coefficients of the wind velocity head ζ_{hp}^{a} and the head resistance of water ζ_{hp}^{w} are the same. The front and after ends of the ice field should be considered as the extended obstacles and then taken $\zeta_{hp}^{a} = \zeta_{hp}^{w} = 2.1$ (Dawson, 2009). The wind velocity $W_h(t)$ in formula (8) should be determined at the level of half of the height of the ice field part rising above the sea level, that is

$$W_h(t) = W_{10}(t)\left(1 + \frac{\sqrt{c_w}}{\chi_0}\ln\frac{0.5\,h_{ice}^{a}}{z_{10}}\right). \tag{15}$$

Modelling of the Ice Field Wind Drift

Wind in the sea is a turbulent flow of an air, the characteristics of which are the velocity and direction change over time. In the problem under consideration, the effects of wind turbulence are not considered. It is assumed that the wind has a constant direction throughout its existence (T_w = 3 days), and the wind action is divided into 3 stages according to the nature of the change in velocity: development (T_s = 0.5 days), constant wind speed W_m = W_{10} for T_c = 1.5 days) and disappearance of the wind (T_d = 1.0 days). At the stage of development, the wind velocity intensively increases, at the stage of constant speed it does not change, and at the stage of disappearance, the wind velocity gradually (linearly) decreases. The dependence of wind velocity on time is taken in the following form (16) and is presented in Figure 3.

$$0 \le t < T_s \quad W(t) = W_m Sin\left(\frac{\pi t}{2T_s}\right), \qquad T_s \le t < T_s + T_c \quad W(t) = W_m,$$

$$T_s + T_c \le t \le T_w \quad W(t) = W_m\left(\frac{T_w - t}{T_w - T_s - T_c}\right). \tag{16}$$

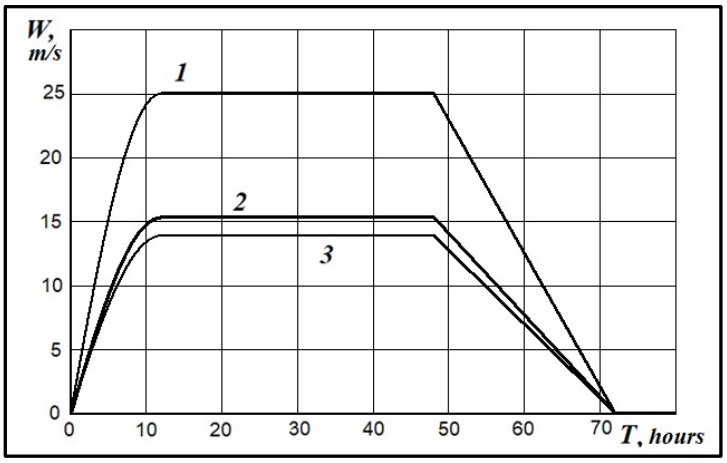


Figure 3. Model dependence of the wind velocity on time. Notations: ***1***- wind velocity on height of 10 m above the sea level, *2* – wind velocity on the ice field upper surface, ***3*** – wind velocity on the windward side of the ice field.

Using the results of parameterization of the components, the equation of the wind drift of the ice field can be represented in the following form

$$(1+k_{11})\gamma_{ice} h_{ice} S \frac{dU}{dt} =$$

$$= \frac{1}{2}\rho_a \left\{\zeta^a_{fr}\left[W_s(t) - U\right]^2 S + \zeta^a_{hp}\left[W_h(t) - U\right]^2 h^a_{ice}\sqrt{S}\right\} - \frac{1}{2}\rho_w\left(\zeta^w_{fr} S + \zeta^w_{hp} h^w_{ice}\sqrt{S}\right)U^2. \tag{17}$$

The velocity of the wind drift of the ice field U depends on the wind velocity $W(t)$ and the sizes of the ice field: surface area S and ice thickness h_{ice}. To analyze these dependencies, the equation (17) was solved in the Mathcad system for the maximum wind velocity W_m = 25 m/s and for the assumed dependence (16) of wind speed on time.

Results and Discussion

To identify the dependence of the wind drift of ice fields characteristics on their dimensions, calculations were made for ice fields with a thickness h_{ice} = 1.5 m and the area $S = 10^3$ m^2, 10^4 m^2, 10^5 m^2, 10^6 m^2 and 10^7 m^2. To identify the dependence of the wind drift of ice fields on their thickness, calculations were made for an ice field with an area of $S = 10^5$ m^2 and with a variation in ice thickness in the range of 0.2 m ≤ h_{ice} ≤ 3.0 m.

Fig. 4 shows the change in the drift velocity of ice fields of various dimensions with time during the action of wind and 180 hours after the wind disappearance. These materials show the drift velocity increases while the velocity of wind increasing and maintenance and then decreases over a long period of time after the wind disappearance. The wind drift velocity increases as the dimensions of the ice field increases. It is possible to explain this effect by following way, the impact of the wind, proportional to the area of the ice floe, increases more intensively than the increase in resistance to drift from the water space.

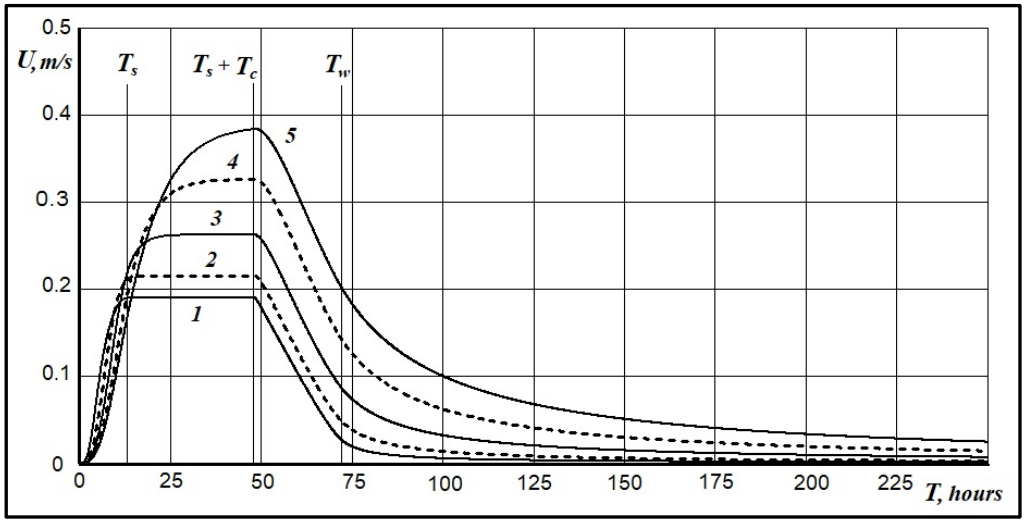


Figure. 4. Dependence of the wind drift velocity of the ice fields with various dimensions on the time after the wind appearance and its disappearance. Notations: area of the ice fields *1* - $S = 10^3$ m^2, *2* - $S = 10^4$ m^2, *3* $S = 10^5$ m^2, *4* $S = 10^6$ m^2 and *5* - $S = 10^7$ m^2. T_s - time of the wind acceleration, T_c- constant wind velocity, T_w - disappearance of the wind.

Fig. 5 shows the dependence of the extent of the drift of ice fields on the time after the appearance and disappearance of the wind. These materials show that wind-induced drift of ice fields continues long after the wind has disappeared. For the largest of the ice fields (area $S = 10^7$ m^2), the drift continues more than 250 hours and exceed 100 km.

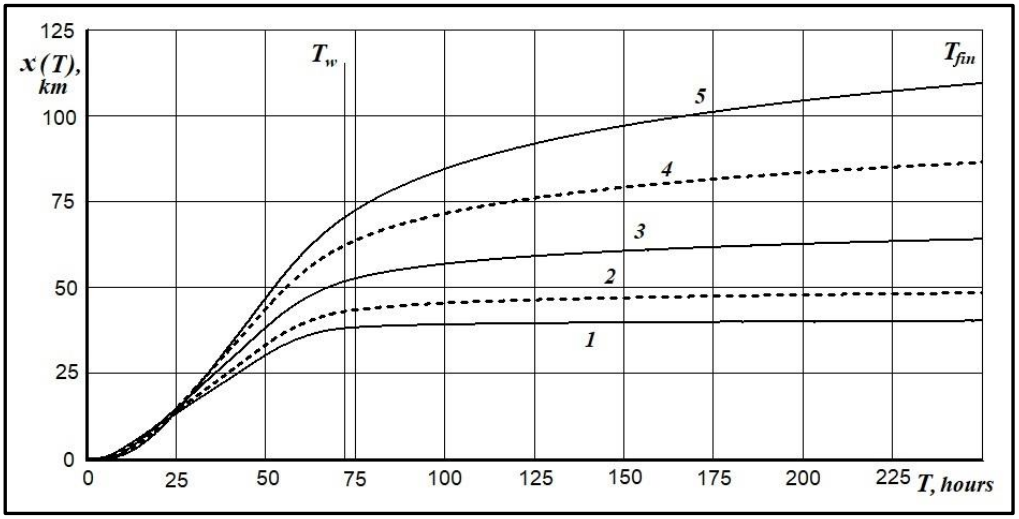


Figure 5. Dependence of the distance of the wind drift of the ice fields with various dimensions on the time after the wind appearance and disappearance. Notations of the ice fields dimensions as on Fig. 4, T_w - time of the wind disappearance.

Fig. 6 shows the dependence of the wind drift velocity of ice fields of different dimensions on the thickness of the ice. These results show that with increasing the ice thickness the wind drift velocity decreases due to an increase in the contribution of drag to the underwater part of the ice field. (The exception is the results for large ice fields and small ice thickness, which requires additional research. Perhaps this effect is due to variation in the ratio of the head resistance and friction resistance to the drift of the ice field.)

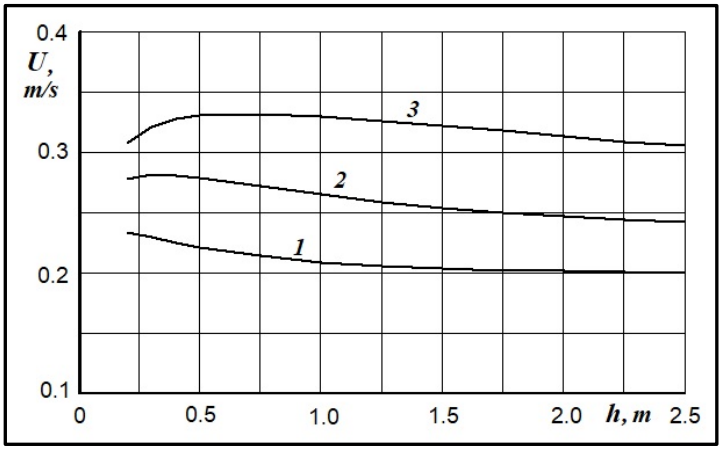


Figure 6. Dependence of the wind drift velocity of the ice fields on the ice thickness. Notations: area of the fields *1* - $S = 10^4$ m^2, *2* - $S = 10^5$ m^2, *3* - $S = 10^6$ m^2.

Fig. 7 shows the dependence of the extent of the drift of ice fields depending on their dimensions and the ice thickness. The results are also ambiguous and require further research: for the largest ice fields, the drift distance increases with increasing ice thickness, and for smaller ice fields, the drift distance after the wind disappears changes little.

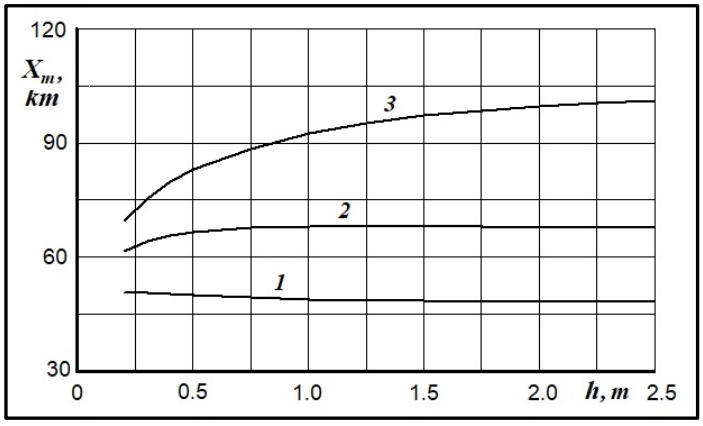


Figure 7. Dependence of the distance of the wind drift of the ice fields on the ice field thickness. Notations: area of the ice fields *1* - $S = 10^4$ m^2, *2* - $S = 10^5$ m^2, *3* - $S = 10^6$ m^2.

Discussion of the Results of Performed Studies

The main result of the work is the development of a mathematical model of the drift of a separate ice field under the wind forcing, which velocity changes in accordance with the natural meteorological process: initiation – acceleration – existence – dying down - calm. The model in this study provided information on the maximum velocity and possible distance of wind drift depending on the dimensions of the ice field and its thickness.

The main qualitative results of the study are as follows:

1. Wind drift of the ice fields can occur for a long time after the wind dying down, and the duration of this "inertial" drift increases with the size of the ice fields.

For the same wind velocity, the wind-induced drift velocity of the ice fields increases with the dimensions of the ice fields.

In real conditions, the Arctic seas are covered with ice fields of various dimensions and are characterized by different concentration. There is reason to assume that individual parts of the open pack ice with a concentration of 9 - 10 points represent the fields to which (as to a whole ice field) the results of the study can be extended. In this case, the "inertial" wind drift can explain the drift and hummocking of the solid ice cover observed by F. Nansen (Nansen, 1999) in the absence of any wind during the Fram drift near the North Pole.

Conclusion and Recommendations

The study is an original approach to the description of the dynamics of the ice cover of the Arctic seas, consisting in the parameterization and study of the features of the movement of an individual ice field and for a close pack-ice fields. This approach in this study is implemented for the wind drift of an ice field that has the shape in plan of a square and the same thickness over its entire area. The original results obtained revealed the dependence of the wind drift characteristics on the dimensions and thickness of an ice fields. In particular, this is an increase in the velocity of drift and its length with an increase in the size of the ice field.

The developed methodology for modeling the wind drift of the ice fields can be used to study other problems of the dynamics of the ice cover of the Arctic seas, in particular, the impact of hummocks and hummocked ice ridge on the drift of ice fields.

The results obtained can be used to control and manage the ice conditions in the water areas of the structure for the development and transportation of mineral resources of the Arctic shelf.

Author Contribution

Vadim K. Goncharov: corresponding author, supervision, conceptualization, investigation, validation, writing, editing.

Polina D. Karpuk: formal analysis, investigation, software, validation, writing.

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SEMICONDUCTOR OPTICAL AMPLIFIERS AS KEY ENABLERS FOR ADVANCED OPTICAL SIGNAL PROCESSING AND NETWORKING

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Abstract
Optical transmission systems are the backbone of modern communication networks, enabling high-speed and long-distance data transfer. Optical amplifiers, such as the Semiconductor Optical Amplifier (SOA) and Erbium-Doped Fiber Amplifier (EDFA), are critical for mitigating signal degradation due to attenuation and dispersion. This study compares these technologies based on structure, performance, and applications, using specific parameters like gain, noise figure, bandwidth, and integration potential. The EDFA excels in long-haul and metro networks due to its high gain, low noise, and ability to amplify multiple WDM channels simultaneously. In contrast, the SOA offers compactness, lower power consumption, and broad gain bandwidth, making it suitable for on-chip and access network applications, particularly with photonic integrated circuits (PICs). A comparative analysis highlights SOA's unique nonlinear properties, enabling advanced functionalities such as wavelength conversion, optical switching, and all-optical logic gates via cross-gain modulation (XGM), cross-phase modulation (XPM), and four-wave mixing (FWM). Experimental evaluation focused on key performance metrics under controlled conditions, including polarization sensitivity and saturation power. While EDFAs dominate traditional amplification, SOAs' multifunctionality and compatibility with silicon photonics position them as vital for next-generation networks, including 5G/6G, data centers, and quantum-secure communications. However, SOA performance is limited by gain saturation and noise at high data rates, requiring careful optimization.
In conclusion, while EDFAs remain essential for long-distance transmission, SOAs offer versatile, compact solutions with significant potential for all-optical systems, provided their practical limits are addressed.
Keywords: Optical transmission systems, Semiconductor optical amplifier (SOA), Erbium-Doped Fiber Amplifier (EDFA).

PLANT-DERIVED CHOLINESTERASE INHIBITORS: A STUDY OF PLECTRANTHUS AMBOINICUS AND ARAUCARIA COLUMNARIS

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Abstract

Alzheimer's disease (AD) is characterized by a gradual decline in cognitive function that is closely linked to disrupted cholinergic neurotransmission. While existing cholinesterase inhibitors like donepezil offer symptomatic relief, their side effects and limited effectiveness prompt the search for plant-based alternatives. This research evaluates the anti-cholinesterase properties of two botanical species: *Plectranthus amboinicus* (Lamiaceae) and *Araucaria columnaris* (Araucariaceae). Methanolic and ethanolic leaf extracts of P. amboinicus, which are known to contain flavonoids, terpenoids, and cinnamic derivatives, demonstrate antioxidant, anti-inflammatory, and enzyme-modulating effects, indicating potential cholinesterase inhibition, albeit with limited direct evidence. Conversely, *A. columnaris* and its related species are rich in phytosterols and terpenoids, with previous research on A. angustifolia revealing significant cholinesterase inhibitory and antioxidant properties; additionally, *A. columnaris* bark extracts are noted for their low toxicity. Through comparative phytochemical analysis and in vitro testing, it was found that both species inhibit acetylcholinesterase (AChE) and butyrylcholinesterase (BChE), with *A. columnaris* exhibiting slightly higher potency. Molecular docking studies indicated the role of key flavonoid and terpenoid components in enzyme binding. Antioxidant activity was observed in both extracts, suggesting synergistic neuroprotective mechanisms that are pertinent to the treatment of AD.

Keywords: Alzheimer’s disease, cholinesterase inhibition, *Plectranthus amboinicus*, *Araucaria columnaris*, antioxidant activity

EFFICACY OF ROSEMARY AND THYME ESSENTIAL OILS ON PEAR (PYRUS COMMUNIS L.) EXPLANT EVOLUTION ON IN VITRO ESTABLISHMENT PHASE

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Abstract

In Tunisia, pear (*Pyrus communis* L.) is a valuable specie, with highly appreciated fruits by consumers. Nowadays this crop is widely threatened by fire blight, a severe bacterial disease caused by *Erwinia amylovora*. Classical propagation techniques (cuttings and grafting) of local pear varieties are delicate and less effective. The use of *in vitro* culture technique would permit rapid propagation and long-term conservation of this crop. Commonly, *in vitro* propagation steps of local pear, mainly initiation or establishment step, is currently achieved by natural or synthetic growth regulators (cytokins and auxins), which are, often, expensive and toxic to handlers and to the environment. Substituting these products with essential oils (EOs) of certain plants could be effective for the initiation step and without harmful effects on humans or environment. Thus, studies were conducted on the effects of rosemary (R_mEO) and thyme (T_hEO) essential oils on the *in vitro* initiation of local pear (*Pyrus communis* L.). The main objective was to evaluate the influence of these two essential oils on the *in vitro* initiation step and the explant establishment and evolution of young cultures through this phase. For that purpose, MS basal medium enriched with various doses (25 µl.L^{-1}, 50 µl.L^{-1} and 100 µl.L^{-1}) of rosemary (R_mEO) and thyme (T_hEO) essential oils were studied. During the initiation phase, rosemary (R_mEO) and thyme (T_hEO) essential oils influenced explant development and reduced bacterial and fungal contaminations, particularly at the highest concentrations. In this context, T_hEO essential oil was found to be more efficient in reducing mainly explants fungal contaminations (8% à 17%). Whereas, R_mEO at 50 and 100 µl.L^{-1} completely inhibited bacterial and fungal contaminations observed on the explants. In addition, R_mEO at a dose of 100 µl.L^{-1} ensured the highest rate of explant establishment (27%).

Keywords: Essential oils (EOs), *in vitro* initiation, local pear, establishment rate, rosemary, thymus.

CLIMATE CHANGE, FOOD SECURITY, AND SUSTAINABLE FOOD PRODUCTION: CHALLENGES AND OPPORTUNITIES FOR RESILIENT FOOD SYSTEMS

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ABSTRACT

Climate change is a significant threat to global food systems, impacting agricultural production, food availability, food access and food stability. A rise in temperature, erratic precipitation, droughts, floods, and extreme weather events have the potential to adversely affect crop production, livestock production, water supplies, and food value chains. The effects of these can also contribute to rising food prices, food losses, and food insecurity, especially for vulnerable groups. The focus of this review is to explore the links between climate change, food security and sustainable food production and to pay special attention to the challenges that climate change poses for agricultural and food systems and the opportunities that arise for developing resilient food systems. New evidence suggests that the ability of the food supply chain to be affected by climate related disruptions may occur across the entire chain—from production, through processing, distribution and consumption.

These risks can be mitigated with sustainable and climate resilient methods. Climate Smart Agriculture, precision farming, efficient water use, crop diversification, better crop varieties, and alternative agricultural production systems will provide opportunities to sustain productivity as environmental conditions change. Also, minimizing food loss and waste, making the food supply-chain more resilient, and using sustainable food-processing technologies are key to food security and alleviating environmental pressures. New technologies like biotechnology, hydroponics, aquarobics, vertical farming and alternative protein production could also contribute to sustainable food production.

Overall, achieving long-term food security requires an integrated approach involving sustainable agricultural practices, technological innovation, efficient resource management, resilient food supply chains, and supportive policies. To ensure food security to meet dietary needs of an ever-growing population, environmental resources need to be preserved for future generations by building climate-resilient food systems.

Keywords: Climate change; food security; sustainable food production; climate-smart agriculture; food systems; resilience; food sustainability; biotechnology.

WHO IS THE MONSTER? POSTHUMAN OTHERNESS AND THE CRISIS OF HUMAN EXCEPTIONALISM IN I AM LEGEND

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Abstract
Francis Lawrence's *I Am Legend* (2007), starring Will Smith as Robert Neville, presents a post-apocalyptic world in which a viral outbreak has transformed most of humanity into infected beings. At first, the film appears to establish a clear distinction between the human and the monstrous, with Neville representing the last remnants of human civilisation and the infected positioned as its threat. However, this distinction becomes increasingly uncertain as the film unfolds. This paper examines how *I Am Legend* challenges the idea of human superiority by questioning who has the authority to define the human and the monstrous. The first objective of the paper is to examine how the film constructs and gradually unsettles the boundary between human and nonhuman identities. The second objective is to explore how Neville's position as the last surviving human exposes the limits of human exceptionalism and forces a reconsideration of the infected as an emerging form of life rather than simply as monsters. The theoretical framework draws primarily on Rosi Braidotti's posthumanist theory and Cary Wolfe's critique of human exceptionalism. Braidotti's understanding of the posthuman subject helps examine the instability of fixed human identities, while Wolfe's work provides a basis for questioning the hierarchy through which human life is privileged over other forms of existence. The paper argues that the film's central tension lies not simply in humanity's struggle for survival but in the collapse of the categories through which humanity defines itself. By shifting the position of the human from dominant species to endangered minority, *I Am Legend* invites a reconsideration of otherness, survival, and what it means to be human.
Keywords: Humanity, Human Exceptionalism, Otherness, Post-apocalyptic world, Posthumanism.

1. Introduction

The distinction between the human and the monstrous has traditionally rested on the assumption that humanity occupies a privileged position within the hierarchy of life. The human is commonly associated with reason, civilisation, language, morality, and social order, while the monster is defined through its apparent failure to possess these qualities. This distinction becomes less secure when the boundaries of the human itself are disrupted. Posthumanist thought challenges the idea of the autonomous and superior human subject by drawing attention to the biological, technological, ecological, and material relations through which human life is constituted. Rosi Braidotti argues that posthuman thought challenges the humanist conception of the unified human subject and unsettles the distinction between the human and its others (Braidotti 2013). Cary Wolfe similarly critiques the assumptions that place the human at the centre of ethical and philosophical consideration. His account of posthumanism calls for a reconsideration of established divisions between human and animal, human and nonhuman, and nature and culture (Wolfe 2010).

The concept of the monster is particularly useful within this framework because monstrosity is not determined solely by physical appearance or biological difference. It is also produced through cultural processes that define what is considered normal and identify those who fall outside that category. Jeffrey Jerome Cohen's *Monster Theory* provides a useful framework for examining this process. Cohen argues that the monster's body is a cultural body, shaped by the fears, anxieties, desires, and prohibitions of the society that produces it (Cohen 1996). The monster, therefore, can be understood not simply as an external threat but as a figure through which a culture expresses and manages its own anxieties. From a posthumanist perspective, this shifts the question from whether a particular figure is human or monstrous to how that distinction is produced and what assumptions sustain it.

The post-apocalyptic world offers a particularly productive setting for examining this unstable boundary. Such narratives are generally situated after a catastrophe that has radically altered the social, political, ecological, or biological conditions of human existence. They frequently depict abandoned cities, damaged infrastructures, fragmented communities, scarcity, isolation, and the breakdown of established systems of order. Yet the importance of the post-apocalyptic setting extends beyond its

representation of destruction. James Berger observes that post-apocalyptic representations are concerned with what remains after catastrophe and with the mixture of wasteland and possibility that follows an imagined end (Berger 1999). The post-apocalyptic world can therefore unsettle categories that previously appeared stable. When established structures can no longer guarantee human dominance, distinctions between human and nonhuman, self and other, civilisation and nature, and life and death become more difficult to maintain.

Francis Lawrence's *I Am Legend* (2007) places this problem at the centre of its post-apocalyptic narrative. Following a viral outbreak that has devastated human society, Robert Neville lives in an almost deserted New York City and understands himself as one of the last representatives of humanity. The infected are consequently positioned as the monstrous other against which Neville defines his own human identity. His scientific work is directed towards understanding and reversing their condition, which reinforces his assumption that the human and the infected belong to fundamentally different categories. As the narrative develops, however, this distinction becomes increasingly difficult to sustain. The infected display forms of social organisation, attachment, communication, and purposeful behaviour that complicate Neville's understanding of them as merely irrational or monstrous beings.

This instability is central to a posthumanist reading of the film. Neville's position as a member of an endangered human minority disrupts the conventional hierarchy in which humanity occupies the dominant position and the nonhuman functions as its subordinate other. The film therefore raises a question about the basis on which the infected can be excluded from the category of the living subject. If they demonstrate sociality, agency, communication, and forms of collective life, their classification as monstrous can no longer be understood as a simple consequence of biological difference. Braidotti's posthumanism and Wolfe's critique of human exceptionalism provide a framework for examining this disruption, while Cohen's theory of monstrosity helps explain how the infected are culturally constructed as the other. Berger's account of the post-apocalyptic condition further clarifies why this process becomes particularly visible after social order has collapsed. The catastrophe does not merely destroy Neville's familiar world; it also destabilises the categories through which he understands humanity itself. *I Am Legend* can therefore be read not only as a narrative of human survival after catastrophe but also as an examination of how the category of the human is produced, defended, and unsettled.

2. The theoretical framework for the analysis

Theorist	**Concept to use**	**Application to *I Am Legend***
Rosi Braidotti	Posthuman subject; instability of the human; human/nonhuman continuum	Examine how Neville’s idea of a stable human identity becomes uncertain
Cary Wolfe	Critique of human exceptionalism; human/animal and human/nonhuman hierarchy	Examine why Neville assumes that human life has greater value or legitimacy
Jeffrey Jerome Cohen	Monster as cultural construction; monstrosity and otherness	Examine how the infected are labelled and represented as ‘monsters’
James Berger	Post-apocalypse; aftermath; what remains after catastrophe	Establish the film’s devastated world as a space where previous social categories are disrupted

3. Discussion: Reconstructing the Human in *I Am Legend*

3.1 The Human as a Category Under Threat

The opening of the film establishes Robert Neville as a survivor of a catastrophe that has fundamentally altered the conditions of human existence. New York, once defined by population, infrastructure, and technological activity, has become almost entirely empty. Neville moves through this space as if he is preserving the remains of a world that no longer exists. His daily routines; broadcasting on the radio, maintaining his laboratory, hunting for food, and social structures that previously defined that order have collapsed.

The film initially gives Neville an uncomplicated identity: he is human because the infected are not. This distinction is sustained through the language he uses to describe them. They are ‘infected,’ ‘Darkseekers,’ and subjects of scientific investigation. The classification is significant because it places

Neville on the side of knowledge and the infected on the side of disease. He observes them, captures them, experiments upon them, and seeks to reverse their condition. The distinction between the human and the monstrous is therefore not simply visual. It is produced through a system of knowledge in which Neville occupies the position of the observer. This becomes problematic when the film begins to show that the infected are not simply mindless biological bodies. Their behaviour suggests memory, attachment, coordination, and intentional action. Neville himself initially refuses to acknowledge these qualities. His assertion that the infected 'don't plan or hate' and 'don't love' attempts to establish a final boundary between them and himself. The statement, however, becomes increasingly difficult to sustain as the narrative develops. The film creates a contradiction between what Neville says the infected are and what the viewer sees them doing.

This contradiction is central to the film's construction of monstrosity. Cohen's argument that 'the monster's body is a cultural body' (1996) is useful here because the Darkseekers acquire their monstrous meaning through the human perspective that classifies them. Their bodies are certainly altered, but their physical difference alone does not explain their position as monsters. They become monstrous because their difference is interpreted as evidence of inferiority, danger, and the loss of humanity. Bowring's discussion of the film similarly places the problem of alterity at the centre of the narrative. Her analysis of 'seeing and interpreting the other' is particularly relevant to Neville's position because the film repeatedly makes the act of looking into an act of classification (Bowring 2015). Neville does not merely look at the infected; he determines what their difference means. His scientific gaze therefore becomes one of the mechanisms through which the boundary between human and monstrous is produced. From a posthumanist perspective, however, that boundary cannot remain stable. Braidotti's conception of the posthuman subject challenges the idea of the human as an autonomous and fixed category. The infected expose precisely this instability. They are not external beings who invade humanity from outside. They emerge from human bodies as a consequence of a human attempt to alter biological life. The catastrophe consequently does not place humanity against an entirely separate species. It transforms humanity into something that can no longer be contained within its previous definition.

3.2 Science, Cure, and the Authority to Define Normality

The film's treatment of science makes this instability more complicated. The Krippin Virus was initially developed as a treatment for cancer. The scientific intervention that promises to eliminate disease instead transforms almost the entire human population. The catastrophe therefore originates within a human attempt to control biological life. Humanity's technological power produces a condition that eventually exceeds that power. Feldman and Clayton (2021) identify this shift as particularly important. Their study argues that the different versions of the story register changing cultural anxieties about biological threats and that the 2007 film moves the source of danger into the domain of genetic engineering itself (Feldman and Clayton 2021). Their argument helps locate the film historically, but the film also permits a more specific question: what happens when the scientific subject becomes unable to determine what counts as a legitimate form of life? Neville's answer is to search for a cure. His repeated assertion, 'I can still fix this,' reveals the assumption behind his research. The infected condition is treated as a problem because it represents a departure from the human state that existed before the outbreak. The objective is not to understand whether the transformed beings have developed another mode of existence. It is to return them to the condition Neville recognises as normal. The word *cure* therefore carries an ideological meaning. It assumes that one state of the body is desirable and another is pathological. Feldman and Clayton point out that Neville's research presumes that the infected want to be cured, effectively treating their transformed condition as a disability that must be corrected (2021). The film does not initially question this assumption because the narrative is organised around Neville's perspective. The viewer is encouraged to understand his experiments as necessary for human survival.

A posthumanist reading unsettles this assumption. Wolfe's critique of human exceptionalism is useful because it asks how the human becomes the privileged category from which other forms of life are judged. Neville's laboratory embodies this hierarchy. The infected bodies are placed behind glass, restrained, examined, and subjected to experimental treatment. Their bodies become objects through which Neville attempts to restore a world in which human beings once occupied the dominant position. The irony is that Neville's own body demonstrates the impossibility of maintaining a simple human/nonhuman division. He is immune to the virus, but his immunity is itself a biological variation produced within the same catastrophe. His body is therefore not simply the untouched human body

standing outside transformation. It is another biological response to the same event.The film consequently presents three different biological positions: the original human condition, Neville's immune condition, and the transformed condition of the infected. None can be understood independently of the others. The apocalypse does not simply destroy the human body. It reveals its capacity for variation as well as its precarity and vulnerability.

3.3 The Infected as an Emerging Social Formation

The most important shift in the film occurs when the infected begin to appear as a social formation rather than a collection of diseased bodies. Neville initially treats them individually as experimental subjects. Gradually, however, the film shows that they possess relationships with one another and respond collectively to Neville's actions. The Darkseeker leader is particularly important. His repeated attempts to locate Neville and retrieve the captured female infected subject suggest that his actions are not reducible to instinctive aggression. He appears to remember Neville's actions and responds to them. The laboratory scene therefore changes the meaning of the infected. They are no longer simply bodies upon which Neville acts. They become beings who act in response to what Neville has done to them. This is where the film's posthuman dimension becomes most visible. The infected cannot easily be placed outside the human because their existence is a continuation and transformation of humanity. Their bodies retain a human origin, while their social behaviour suggests a new form of collective existence. They occupy a position between categories.

Braidotti's arguement is useful here because it allows identity to be understood as relational and materially embodied rather than as a fixed essence. The infected do not need to be declared 'new humans' for the film to challenge human exceptionalism. It is sufficient that their existence demonstrates that the human condition can change without disappearing completely. The distinction between *human* and *infected* therefore begins to resemble a distinction between *normality* and *difference*. Neville's scientific language converts difference into pathology. His task is then to eliminate the difference rather than to reconsider the category through which it has been defined. This is also where Cohen's theory of monstrosity becomes productive. The monster exists at the boundary of categories and threatens the stability of those categories. The infected occupy exactly this position. They are recognisably derived from human beings but cannot be accommodated within Neville's definition of humanity. Their existence consequently creates anxiety not simply because they are dangerous, but because they make the category of the human uncertain.

3.4 Neville and the Reversal of the Monster

The film becomes more ethically complicated when Neville's treatment of the infected is considered from their perspective. His actions are presented for much of the narrative as necessary acts of survival. Yet the same actions can be described differently if the infected are regarded as subjects rather than objects. Neville captures them. He confines them. He exposes them to experimental procedures. He kills them when they attack him. He regards their bodies as material for scientific research. Within his own understanding, these actions are justified because the infected threaten humanity. Once the infected are recognised as a social group with their own relationships, however, the same actions begin to resemble persecution. This reversal is important because it shifts the question from whether Neville is justified in defending himself to whether his definition of the infected has made their suffering invisible. Feldman and Clayton make a related observation in their discussion; the stories repeatedly construct the infected as an Other and eventually reverse the position of Neville and those he has persecuted. They describe this movement as a shift in which the protagonist moves from Othering the vampires to being Othered by them (Feldman and Clayton 2021). The 2007 film does not develop this reversal as fully as Matheson's novel, but the alternative ending makes it considerably more visible.

The scene in which the Darkseeker leader enters Neville's laboratory is therefore crucial. His objective is not simply to attack Neville. He comes for the female subject Neville has captured. The scene allows the viewer to reinterpret the laboratory from the perspective of the infected. What Neville understands as medical research can now be seen as the captivity of a member of another community. Neville's position consequently becomes unstable. He remains biologically human, but his actions can be interpreted as monstrous. The infected remain biologically altered, but their actions can be interpreted as protective and social. The categories have not simply been reversed; their supposed moral certainty has been removed. This is precisely the point at which the film moves beyond a conventional survival

narrative. The central conflict is no longer simply between two groups fighting for existence. It becomes a conflict over the right to define what kind of existence deserves recognition.

3.5 The Post-Apocalyptic City and the Loss of Human Centrality

The film's treatment of New York City reinforces this argument. The empty city is not merely a symbol of loneliness. It represents the withdrawal of human authority from a space that was once organised almost completely around human activity. Neville's movement through the city initially suggests control. He drives through empty streets, hunts animals, enters abandoned buildings, and uses the remaining infrastructure to sustain himself. Yet the longer he remains there, the clearer it becomes that the city no longer belongs exclusively to human beings. Vegetation grows through the built environment. Deer occupy streets and abandoned spaces. Animals move through areas that previously belonged to human traffic. At night, the infected claim the same spaces that Neville controls during the day. The city therefore becomes a shared but contested environment. This environmental transformation matters to the film's posthuman argument because the collapse of civilisation does not produce a simple absence. Other forms of life become more visible. The disappearance of human crowds makes the nonhuman elements of the city perceptible in ways that ordinary urban life had concealed.

Neville's loneliness is therefore also a loss of human centrality. He is surrounded by the material remains of human civilisation but no longer supported by the social system that gave those remains their meaning. His broadcasts—'You are not alone'—are attempts to restore a human community that no longer exists. The post-apocalyptic setting thus changes the meaning of survival. Neville is not simply surviving *after* the end of civilisation. He is trying to preserve an idea of civilisation in an environment that has already moved beyond it.

3.6 The Two Endings and the Limits of the Posthuman Argument

The two endings are crucial because they reveal a tension within the film's representation of humanity. The theatrical ending ultimately restores a human-centred narrative. Neville sacrifices himself, Anna and Ethan escape with the cure, and his death is transformed into a story of human salvation. His final status as a 'legend' therefore re-establishes the value of his actions from the perspective of the surviving human community. The alternate ending produces a different ethical effect. Neville survives the encounter with the Darkseekers and is forced to recognise that they have a social order and that the beings he has been experimenting upon are not simply objects of scientific investigation. The scene makes visible the possibility that Neville has misunderstood the world he has been trying to save. Feldman and Clayton's comparison of the adaptations is useful here because they note that the theatrical version moves away from the more radical reversal found in Matheson's original story, while the deleted ending comes closer to the original's recognition that the protagonist may occupy the position of the monster.

The difference between the endings therefore matters for central argument of this study. The film does not offer a consistent posthuman position. Instead, it opens a posthuman question and then partially closes it. The alternate ending destabilises the human/monster distinction, while the theatrical ending restores a more conventional hierarchy in which Neville's sacrifice confirms the value of the human community. This contradiction should not be treated as an inconsistency that invalidates the posthuman reading. It reveals the limits of the film's engagement with posthumanism.The film can imagine the collapse of human superiority, but it remains attached to the emotional and ideological security of human survival.

3.7 Reconsidering the Human

The significance ultimately lies in the fact that the film makes the human category visible as something that has to be continually reconstructed. Neville's humanity is sustained through his distinction from the infected. His scientific work depends upon treating their bodies as objects. His survival depends upon viewing their existence as a threat. His final heroism depends upon the belief that preserving humanity is an unquestionable good. The film nevertheless provides evidence that complicates each of these assumptions. The infected originate in humanity. They develop social relations. They respond intentionally to Neville. They occupy the same environment as the surviving humans. Their bodies demonstrate that biological transformation does not produce a simple opposition between human and nonhuman. Braidotti's posthumanist idea helps explain why this matters. The human subject cannot be understood as an autonomous and unchanging entity when its biological existence is continuously

shaped by other bodies, technologies, environments, and forms of life. Wolfe's critique of human exceptionalism adds an ethical dimension to the argument: the problem is not simply that Neville misidentifies the infected, but that his definition of humanity determines whose life can be recognised, studied, protected, or sacrificed. Cohen's concept of monstrosity completes this argument by showing that the monster is produced at the limits of cultural categories. The infected become monstrous because they expose the instability of the human category. Once their perspective becomes visible, Neville's position is transformed as well. The film therefore shifts the meaning of apocalypse. The catastrophe is not only the destruction of human civilisation. It is the destruction of the certainty with which humanity once defined itself. Neville survives physically, but the category of the human that gives meaning to his survival is no longer secure. The film consequently presents a paradox at the centre of posthuman existence: humanity attempts to preserve itself by excluding what it considers nonhuman, yet the very beings it excludes emerge from humanity itself. The infected are not simply the end of humanity. They are evidence of what humanity can become. The film's most significant challenge to human exceptionalism emerges from this possibility. Once the human is understood as a changing biological and cultural condition rather than a fixed essence, the boundary between human and monster can no longer be treated as permanent. The film does not resolve this problem. Its theatrical ending ultimately restores the human-centred order, while its alternate ending leaves that order unsettled. What remains significant is the tension between these two possibilities. Therefore, it asks the viewer to consider whether survival means preserving an existing definition of humanity or recognising that survival itself may require a different understanding of what counts as human.

4. Conclusion

The film ultimately raises a question more difficult than the question of who survives. It asks what remains of the idea of the human when the boundaries separating human from nonhuman can no longer be taken for granted. Neville begins by assuming that humanity is the norm and that the infected represent its corruption. His scientific project is built on this assumption. They are diseased, he is healthy; they must be cured, while he must survive. Yet the film gradually makes these distinctions less secure. The infected develop forms of agency and social organisation, while Neville's own actions begin to appear less clearly aligned with the moral order he believes he is defending. This raises a philosophical problem at the centre of the film: is being human a biological condition, a set of behaviours, or a position from which other forms of life are judged? If the infected retain forms of memory, attachment, communication, and sociality, on what grounds can they be excluded from consideration as subjects? Conversely, if their transformation is understood as the emergence of something different, does difference necessarily imply the loss of human value? The film does not provide definitive answers. Its significance lies partly in leaving these questions unresolved.

Read through Braidotti and Wolfe, this uncertainty has implications for the idea of human exceptionalism. The film presents humanity not as a stable and universal category but as a position that becomes particularly visible when it is threatened. Neville's status as one of the last surviving humans gives him a heightened sense of what must be protected, but it also reveals how easily the preservation of "humanity" can become a justification for excluding those who no longer fit its established definition. The question, then, is not only whether the infected are human. It is who has the authority to decide. The film's two endings deepen this philosophical tension. The theatrical ending restores a recognisable human order through Neville's sacrifice and the survival of the cure. The alternate ending makes the infected more legible as subjects and places Neville's actions in a more troubling ethical frame. Neither ending completely settles the question of what kind of life deserves to survive. Instead, *I Am Legend* leaves an uncomfortable possibility behind: perhaps the real threat is not the appearance of a new form of life, but humanity's inability to recognise life once it no longer resembles itself. This is where the film's posthumanist significance lies. It does not simply replace the human with the nonhuman or declare the two equivalent. It asks what assumptions make such a hierarchy possible in the first place. If the human can become the Other, and the Other can begin to display qualities once considered exclusively human, then the category itself demands examination. *I Am Legend* ultimately leaves its audience with a question rather than a resolution: when humanity is forced to confront a form of life created from its own biological and scientific history, can it recognise that life without first measuring it against an image of itself?

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TRAUMA IN POST-INDEPENDENT AFRICAN FICTION: A PSYCHOANALYTIC READING OF ISHMAEL BEAH'S LITTLE FAMILY.

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Abstract
African literature, among other functions, portrays the lived experiences of people born and raised in societies marked by conflict, violence, and social upheaval. Drawing on Sigmund Freud's psychoanalytic theory, this paper examines the psychological effects of the traumatic postcolonial conditions that Ishmael Beah implicitly and explicitly portrays in *Little Family*. The study explores how the writer constructs characters whose physical and psychological suffering illuminate the novel. It argues that Beah, like many African novelists, critiques the disillusionment that followed the political independence of many African countries and exposes the persistent social and political crises that continue to shape postcolonial realities. The analysis reveals that these conditions give rise to trauma and "nervous conditions" that profoundly affect characters' mental well-being, particularly that of the youth.
Keywords: Trauma, Psychoanalysis, post-independence Africa, disillusionment, Ishmael Beah

METADISCOURSE STRATEGIES IN JOE BIDEN'S MARCH 1, 2022 SPEECH: A LINGUISTIC ANALYSIS

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Abstract
This study investigates the use of metadiscourse strategies in Joe Biden's speech delivered on March 1, 2022, with the aim of examining how linguistic resources are employed to organize discourse, engage the audience, and convey the speaker's stance. Drawing on the metadiscourse framework, particularly the distinction between interactive and interactional resources, the study analyses the linguistic devices through which Biden structures his arguments, establishes relationships with his audience, and strengthens the persuasive dimension of his speech. A qualitative approach, complemented by quantitative analysis, is adopted to identify, classify, and interpret the metadiscourse markers occurring in the speech. The analysis focuses on such categories as transitions, frame markers, evidentials, code glosses, hedges, boosters, attitude markers, self-mentions, and engagement markers. The study is expected to reveal that metadiscourse plays a significant role in enhancing the coherence, interpersonal dimension, and rhetorical effectiveness of Biden's political discourse. The findings further suggest that the strategic use of metadiscourse enables the speaker to guide the audience through his arguments while simultaneously expressing certainty, emphasizing key propositions, and fostering a sense of solidarity and engagement. The study contributes to the understanding of metadiscourse as an important linguistic and rhetorical resource in contemporary political speeches.
Keywords: metadiscourse strategies, political discourse, linguistic analysis, political speech.

DERANGEMENT OF SCALE: PLANETARY ECOCRITICISM AND ANTHROPOCENE FORM IN RICHARD POWERS'S PLAYGROUND

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ABSTRACT
Richard Powers's *Playground* (2024) weaves together ocean ecology, artificial intelligence, and the contentious future of the Pacific atoll of Makatea, creating a narrative that questions humanity-sized ways of knowing the environment. This study investigates the novel in light of Timothy Clark's notion of the "derangement of scale" which refers to the challenge of representing phenomena in ecology that are larger in scope than what is typically intelligible to the human imagination and ethical practice. The study takes a planetary ecocritical perspective, based on the works of Clark, to argue that Playground is not merely a representation of the Anthropocene ecological crisis, but also formally produces its scalar instability. For example, Evie Beaulieu's interactions with octopuses and pygmy seahorses place the ocean in the lived world and in a world of systems of acidification, biodiversity loss and planetary change. This work is an attempt to extend Clark's theory of scalar derangement, connecting it to Powers's oceanic fiction and situating *Playground* as one of the important planetary ecocritical narratives in current climate fiction.
Keywords: *Anthropocene, ecocritical, acidification, biodiversity, planetary*

INTRODUCTION
The problem of representation is a problem that is different from the ecological issues that can be observed in nature writing of the past. *Ecocriticism on the Edge: The Anthropocene as a Threshold Concept* (2015) by Timothy Clark states that the Anthropocene is a crisis in inherited habits of interpretation since it is "a radical difference in spatial and temporal scale." Clark's notion of scale framing is particularly significant because an environmental phenomenon may have different ethical and political implications when viewed from another scale. What may seem like a small event to one person may seem like a disaster to the collective or geological understanding of the same action. *Playground* (2024) by Richard Powers is a collection of marine science, artificial intelligence, technological capitalism, colonial past, island politics, and the future of Makatea in French Polynesia. In its characters' experiences, it always comes back to the issue of local experience and planetary processes. This article proposes that Playground is a derangement of scale formally, in Clark's terms. The novel's importance is not just its depiction of ecological crisis, but the fact that it will not keep the reader at one level of interpretation. A planetary ecocritical reading, however, can see the instability as the formal result of trying to render things that are not possible to manage in the usual human dimensions.

REVIEW OF LITERATURE
Playground (2024), what Richard Powers has penned in his novel, is rich in its relationship between humans, technology and nature. The novel deals with the struggle between technological aspiration and the protection of the environment. The novel has recently been the focus of academic study with a focus on trauma, technology and cultural resistance. Bezrukov and Bohovyk (2025) have explored the human and natural stories in the Anthropocene era. They show how Powers challenges anthropocentrism and how he shows the repercussions of ecological carelessness, and a more symbiotic relationship with the natural world. They evoke Powers's irresistible tale of personal miseries, environmental concerns, fears of the Anthropocene, cultural fallacies, the misplaced trust in technology that can lead readers to contemplate their own culpability in the global environment, the need for environmental responsibility and the pressing need for climate action and a sustainable future.

Lodhi, Bibi, and Andleeb (2025) have explored critical study on the technology, identity and construction of memory. The authors provides reflections on the effects of technology and digitalization on the social and psychological life of people in a post-digital society as seen in literature. The study explicitly states that the text they have chosen, *Playground*, is a technological solution to creating a way to preserve memories; however, it challenges the validity of such a solution and suggests that identities are not eternal, and that over time, they change constantly due to the intervention of memories, time and technology. In the same way, Oppermann (2026) describes the nonhuman memory in terms of oceanic and algorithmic articulations, considering marine life and computational systems as active agents in the process of memory, relation and world-making.

Similarly, Powers also represents blue anti-human exceptionalism. Analysis have been made constituting this theme. Cristofaro (2026) for example, investigates how ocean species are able to "play", to perceive and to take care of their mothers. The author emphasizes that the novel uses the 'ecological sublime' effect by creating the semantic fields of amazement and incomprehensibility regarding many activities occurring below the sea surface. Thus, the novel demonstrates that there are things that cannot be demanded of humans, if it comes to human and non-human aspects, and they are the things that cannot be enumerated.

Meanwhile, another issue that is worth, but not mentioned often, is the issue of Posthumanist vulnerability and entanglement. Taking inspiration from critical posthumanist theory, Bueno (2025) looks at how the novel carries forward aspects of Powers's signature themes and storytelling techniques, and how it also creates new themes and creative opportunities. The author's work focuses on the novel whose main subject is the wonders of the oceans—which despite sustaining life on Earth face unprecedented threats. In conclusion, the author's work shows that by emphasizing entanglement, instilling wonder and awe of the oceanic beings, and incorporating indigenous knowledge systems, and adding a twist at the end that upends readers' expectations, the novel serves as a message on how to navigate the uncertain times.

Eventhough there exists an increasing amount of scholarly literature on *Playground*, previous analyses tend to focus on trauma, technology, cultural resistance, identity, memory, blue humanity, blue anti-human exceptionalism and posthuman vulnerability. Much less literature has been written concerning the exploration of derangement of scale, planetary ecocriticism and anthropocene form. Hence, the objective of this study will be to bridge this gap in the study by critically analysing the novel *Playground* in the light of planetary ecocriticism and deranged scale and Anthropocene studies.

RESEARCH AND FINDINGS

The Problem of Scale: Timothy Clark

This study adopts a central theoretical position that ecological questions are inextricably linked to questions of scale. Conventional literary interpretation has often been conducted on an individual and local level. The issue is that ecological phenomena have to be addressed at various levels simultaneously. This is what Clark meant by 'derangement of scale'. *Playground* is a novel with an unusually strong example because nearly all of their major conflicts are set up by incompatible scales. The individual is never only an individual. The island is always more than just an island. The sea is never just a backdrop. Technology is never just a tool. Even the local democratic process of the referendum is never just that. Both function within larger systems which continually challenge the human-scale event's apparent limits.

Makatea: From Island to Planetary Formation

Makatea is said to have started out as a seamount under the sea and to have been slowly modified by coral and other life processes. Human political time is also day-to-day, week-to-week, election-to-election, contract-to-contract, and development schedule-to-development schedule. Colonial history is a trans-generational process. Geological time is on the order of millions of years. Ecological time involves coral growth and species adaptations, reproduction, and environmental change on varying scales. This leads to an instant case of scalar derangement. In the referendum the seemingly minimal vote is conceptually vast since it is on the being of a place that is part of planetary history. Further, the "isolation" of the island is scale dependent. Closeness to the centre is an integral part of community identity at the local level. Remoteness is a resource at the corporate level. On the colonial level distance

is a power structure. On the planetary scale, the island turns into a weak point of the Pacific ecosystem. This changing of meaning is an example of Clark's scale framing.

The Ocean as a Scalar Environment

Ocean is seen as an active and dynamic system where human and non-human lives are connected. Evie Beaulieu swims amongst the octopuses and between the fish and other sea creatures. She is not viewing the reef from an objective outside standpoint, rather, she is physically located within the reef. Furthermore, microscopic and planetary coexist. An octopus is an individual animal that can interact and be intelligent, but its life is enmeshed in a complex marine system, which humans can harm, without directly perceiving the effects. The reef is thus a point of contact between scales. There is no solution in ecological crisis offered by the sense of wonder in Evie. This doesn't mean she removes the ecological uncertainty from her scientific knowledge. The closer the individual has a look, the larger the ecological system extends. Marine organisms have their own means of locomotion, adaptation, perception and survival. Their presence challenges the notion that it is the human being as the natural centre of the meaning of ecology. The reef is therefore a scalar environment; one that is "close enough to touch," "too hard for science," and "too vast to exist on the scale of the planet.

Marine Play to Ecological Crisis

The concept of scale as Timothy Clark defines it, becomes more important when one reads the title *Playground*, as the word “playground” at first seems to point to an environment in which people play, not to a place that is boundless or out of control, but rather a human-sized space, synonymous with childhood and recreation. Evie Beaulieu says that while diving in the Raja Ampat archipelago she becomes “like a babe in Toyland, set loose in the greatest playground any child had ever seen,” and then, “playing hide-and-seek with octopuses and tag with pygmy seahorses” (Powers 112). In the meantime Powers writes that the reef “is a metropolis built by billions of architects almost too small to see—and at night a billion different psychedelic missions, all dependent on each other” (112). The seemingly playful interaction thus leads to an ecological system that is more complex than the individual can see. The metaphor of the playground is a scalar mismatch: a familiar human concept is deployed in an environment that cannot be reduced to human biological, spatial and temporal processes.

Scalability and Seasteading

From Todd Keane's point of view, the ocean is a place of possibilities. But to the people of Makatea, the seasteading idea is not simply a technological play, but one that has the potential to affect their home, job, political independence, environmental access, collective memory, and future. It is this scalar difference that Powers emphasizes by juxtaposing the present-day proposal against the long geologic and ecological history of Makatea. Thus, the referendum creates an extraordinary mismatch in time and space: the decision is made in an instant, but it has consequences that can reach across generations, the object of concern is part of planetary ecological systems and the decision-making body is a relatively small local community. In this way, the Makatea referendum is a formal instance of Timothy Clark's notion of “derangement of scale” – a planetary scale ecological and technological issue made human scale, as a local political choice.

Children, Future Generations, and the Enlarging of the Political Scale

The referendum becomes relevant when the issue of participation of children comes up. Of course, adults have the current political power, yet children will be living for a lot longer in the results of current decisions. Rafi and Ina's anxiety about their children's vote is especially telling because they know that their children have some real claim to the island's political future, but they can't simply tell them to vote; they don't know what the proposed project will turn out to be (Powers, Playground, p. 112). The residents can present documents, hear experts, ask questions of artificial intelligence, and discuss the proposal; but none of these exercises can remove the uncertainty created by the mismatch between a short-term political decision and a long-term ecological process (Powers, Playground p. 134). Thus, the referendum can be considered an Anthropocene political form, which performs the process of packaging uncertainty and complexity of the planet into a human institutional action.

Profunda and technology of scale management

Profunda, the AI system is introduced to the residents of Makatea as a technological instrument through which they can delve into the potential impacts of the proposed project. With the central question, it is

not just about whether AI is smart enough, but about whether computational scale can solve ethical scale. So, scalar problems are not always solvable by increasing the amount of information available. Profunda can collect data about the economy, environment, infrastructure and future of Makatea, but there's no computational database that can completely remove the differences between a statistical projection and the reality of an island community. The novel's discussion of Profunda is thus in line with the novel's treatment of scale in general: technology is not a way of getting rid of scalar disorder, but rather of reorganizing it. In this regard, the novel differentiates between information and responsibility.

Todd Keane and the Fantasy of Escape from Scale

It is Todd Keane's character that sets *Playground*, as technology is his medium of expression. There is a search for a technology that isn't limited by social, political, and geographical scales. His later passion for seasteading takes this virtual world into the real world. The transfer from digital platform to floating settlement is consequently not a coincidence; both projects are based on the same premise that space can be redesigned and limitations can be overcome. Todd's project is a project for liberation from the current political and social frameworks, but it is a project that can only function if it enters into a place that has been already structured by history, community, ecology, and colonial histories. In this way, *Playground* reveals the hope for a technological innovation that could help human beings transcend the scale of current systems, when in fact Todd's projects quickly become embroiled in scales beyond his means and question the autonomy of technology.

Colonial Scale and the Persistence of the Past

Any clear distinction between local democracy and global technological capitalism is complicated by the island's relationship with France and the mining history of the area, as well as the influence of outside political and economic institutions. This historical dimension is important because colonialism itself is scalarly structured: decisions of political leaders in other parts of the world can have significant consequences for the well being of people living in far-flung islands, economic systems can link local landscapes to global markets and extractive industries can shape the environment to which residents have little control. The seasteading idea thus has the potential of creating a new version of the old colonial model with new technology. While their local decision may sometimes make the difference whether a specific project goes ahead or not, it can never be all, that determines the consequences that are created by global markets, technological infrastructures, oceanic systems, ecological change or historical forces. Such tension would render the idea of derangement of scale more productive. Makatea is at the same time local community, postcolonial place, ecological place, economy place, and a node place in the planetary system.

Narrative Form as Scalar Derangement

The novel's ecological, technological and political antagonisms are not set in a coherent narrative scale; rather, it is a braided narrative in which different times and places, characters and knowledge modes are all relevant to one another. Todd's technological past resonates with the political and ecological future of Makatea; Evie's marine experiences link individual perception with planetary ecology; Rafi and Ina's personal histories link with the island's colonial and political past; and Profunda links between local political deliberation and global computational systems. Life therefore intersects with the characters not only through their personal interactions, but also in greater ecological, technological, political and historical systems. A personal memory becomes entangled with a historical event; a local political decision becomes planetary; a marine encounter becomes a whole ecology; an AI tool becomes entangled with political decision making; and a technological project becomes recognizable as part of a longer history of colonial intervention. The reader is not simply presented with scalar derangement as a theme, but the reader experiences scalar derangement through the structure of the narrative itself.

Scale, Responsibility, and the Individual

Todd Keane has an incredible individual power, and his technological riches allow him to launch projects whose impacts are not just personal, but also ecological, political, economic and historical; however, he cannot entirely master the ecological, political, economic and historical systems he enters. The people of Makatea, on the other hand, are far less economically and technologically strong but their decision gains political relevance because of the direct impact of the proposed development on their homes, community and their ecological surroundings. Evie has scientific expertise to engage with and understand marine systems, but not the power to control the ocean; Profunda has huge computing power,

but cannot solve the ethical dilemma about the potential impact of the planned project. *Playground* is a testament to the fact that individual agency is basically scale dependent: what might seem a small local decision might have a large impact on a broader ecological or political system, and what might seem like a huge action on one scale might seem insignificant on another.

From Scalar Derangement to Planetary Ecocriticism

Planetary ecocriticism has been linked to the ecological criticism expanding from local to global or planetary level. Throughout the novel there is a constant shifting of scale, and no one spatial, temporal, or conceptual frame is ever adequate. Evie's experience with marine life is linked to larger ecological issues, and Makatea's political turmoil cannot be divorced from colonial past and planetary environmental issues. It is ultimately the planetary ecological awareness that is not achieved by taking a departure from what is local to what is global, but by acknowledging that the relations between different scales of spatial and experiential awareness are unstable and often contradictory. In this way, scalar derangement turns into a scaffold for planetary ecocriticism, allowing *Playground* to figure the planetary as less of a remote abstraction and more of a planetary constantly under construction through the entanglements of bodies, places, histories, technologies, oceans, and ecological processes.

CONCLUSION

Richard Powers's *Playground* is a novel which questions about the nature of what is hard to represent loom large, in particular the ecological and technological processes that are not human-scale. The environment is at once local and planetary, immediate and geological, individual and collective. Ecocriticism is thus not only a discipline that needs to be expanded in its field of vision but one that has to learn to think across incompatible scales. The reader is constantly asked to make the transitions from the individual to the collective, from the local to the planetary, from the biological to the technological, and from the immediate to the geological. There is no one dominant viewpoint that is let to fixate the meaning of the ecological crisis. This is *Playground*'s key contribution to planetary ecocriticism. Further, the ocean is not just a picture, a source, or a technological platform but a large relational system in which human life is situated. Makatea is not just a small island under the threat of a big project, it is a local expression of planetary processes. Evie's reef is not only a beautiful place, but it's also a place where intimate experience and planetary ecology meet. The referendum is not just a local political event, it is an effort to translate planetary uncertainty into collective human action. *Playground* is an example of deranged scale's literary possibilities. It is not a solution to the conflict between local and planetary views, but rather makes it formally visible. It is the very refusal to offer a single scale for the comfortable understanding of the Anthropocene that makes the novel so important. Finally, the novel proposes that the Anthropocene is not just a climate and biodiversity crisis, a technological and/or political organizational crisis, but a crisis of proportion. People are forced to operate at scales beyond their perception, on systems that make decisions at scales that are long-term with respect to the human lifespan, and in ecological systems that have histories both older than themselves and longer than their own. This is the state that Clark's derangement of scale renders legible. Powers's *Playground* puts that state into narrative mode.

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THE LANGUAGE OF SCHOOL PANDEMONIUM: CREATING HUMOR AND CHARACTER IN JEREMY STRONG'S 'PANDEMONIUM AT SCHOOL'

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Abstract
Children's literature frequently employs humor to transform familiar social situations into imaginative and emotionally engaging experiences. School fiction is particularly productive in this respect, as the school environment provides a recognizable framework of rules, authority, discipline, and interaction between adults and children. Jeremy Strong's 'Pandemonium at School' offers a distinctive comic representation of this environment, in which ordinary educational situations acquire an element of absurdity and unpredictability. This study examines the linguistic means through which humor and characterization are constructed in the novella.
The purpose of the research is to identify the principal lexical, syntactic, and pragmatic features that contribute to the comic effect of Strong's narrative and to determine their role in representing teachers, pupils, and the school environment. The analysis employs linguistic-stylistic, contextual, and structural-functional approaches, focusing on colloquial language, expressive vocabulary, exaggeration, repetition, exclamatory structures, imperatives, questions, and dynamic dialogue.
The analysis suggests that Strong's humor is closely connected with the contrast between the conventional language of institutional authority and the more spontaneous, expressive, and unpredictable language of comic interaction. Colloquial expressions and emotionally marked vocabulary contribute to the informal atmosphere of the narrative, while exaggeration and repetition intensify otherwise ordinary situations. Dialogue plays a particularly important role, allowing characters to reveal their personalities through rapid exchanges, unexpected responses, misunderstandings, and verbal contrasts. These linguistic strategies also contribute to the comic transformation of the school environment: rules and authority remain present, but their seriousness is repeatedly challenged through language and interaction.
The study argues that in 'Pandemonium at School', humor is not merely an entertaining feature of the narrative. It constitutes an important linguistic and character-building strategy that enables Strong to present school life as dynamic, unpredictable, and open to imagination. The comic language of the novella thus contributes simultaneously to characterization, narrative movement, and the creation of an accessible and engaging reading experience for children.
Keywords: children's literature, Jeremy Strong, humor, comic language, colloquial language, dialogue.

"SO IT GOES": A LACANIAN READING OF THE SLAUGHTERHOUSE-FIVE BY KURT VONNEGUT

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Abstract
Kurt Vonnegut's *Slaughterhouse-Five* (1969) is a postmodern American novel that blends science fiction, autobiography and historical fiction. The novel recounts the experiences of Billy Pilgrim, a World War II soldier who becomes unstuck in time after surviving the firebombing of Dresden. War trauma and its effects on the human psyche have been widely analyzed in postwar literature and examined through various critical lenses, including Freudian psychoanalysis and trauma theory. However, Kurt Vonnegut's novel has rarely been examined through a Lacanian Lens. This paper offers a Lacanian psychoanalytic reading of the novel, employing Jacques Lacan's concepts of the three orders namely the Imaginary, the Symbolic and the Real, repetition automatism and objet petit *a* to explore how trauma affects Billy Pilgrim. The paper argues that Billy Pilgrim's traumatic experiences, particularly the firebombing of Dresden, cause the Real to collide with the Symbolic and Imaginary orders, shattering his coherent sense of self. Furthermore, his pursuit of Tralfamadorian philosophy, with its acceptance of all moments as simultaneously existing, functions as a desperate quest for the objet petit *a*, attempting to fill the void left by trauma and to restore a sense of meaning. Ultimately, the findings suggest that Vonnegut's fragmented narrative confronts the unspeakable horrors of war indirectly.
Keywords: Vonnegut; Billy Pilgrim; Lacan; The three orders; Objet petit *a*; Repetition; *Slaughterhouse-Five*

TOWARD ROBUST AND ADAPTIVE IMAGINED SPEECH RECOGNITION SYSTEMS FOR BRAIN-COMPUTER INTERFACES

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ABSTRACT
Brain-computer interfaces (BCIs) have drawn growing interest as a way to let the brain communicate directly with external devices, bypassing muscles and nerves altogether. This has real value for assistive technology, especially for people with severe motor or speech impairments [1,2]. Among the paradigms researchers have tried, imagined speech stands out as one of the more promising. It refers to silently forming words in the mind, with no sound and no visible movement of the mouth or throat. Compared to motor imagery, which usually maps to a small set of movement commands, imagined speech opens the door to a much wider and more natural vocabulary for communication.
Most work on decoding imagined speech relies on EEG, a non-invasive method with strong temporal resolution and comparatively easy setup. Even so, the problem is far from solved. EEG signals are weak, easily corrupted by noise and artifacts, and vary considerably from one person to another and even from one session to the next for the same person. On top of that, the neural mechanisms behind internally generated speech are still poorly understood, which makes the signals themselves hard to interpret.
Building a working imagined speech recognition system means digging deeper into what these speech-related neural patterns actually look like, and designing computational methods that can make sense of noisy, variable EEG data. Progress here would move BCI research closer to communication systems that are intuitive, fully non-invasive, and tailored to the individual user, giving people who cannot speak or move a genuine alternative channel for interaction.
Keywords: Brain-computer interface, imagined speech, EEG, speech decoding, assistive technology.

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EFFECTIVENESS OF INTERACTIVE SENSORY SYSTEM «BRIOLIGHT» IN COMPLEX REHABILITATION OF CHILDREN WITH PSYCHOMOTOR SPEECH DELAY

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ABSTRACT

Objectives. The aim of this study was to evaluate the effectiveness of the interactive sensory system «Briolight» in the comprehensive rehabilitation of children with psychomotor speech delay (PMSD).

Methods. A prospective comparative study included 40 children aged 4–8 years with PMSD (ICD-10: F80, F70). Participants were randomized into four equal groups: three intervention groups — fine motor training using Briolight optical sensor (Group 1), gross motor training using Briolight interactive floor/wall (Group 2), speech therapy using Briolight interactive mirror with audio feedback (Group 3) — and one control group receiving standard non-digital rehabilitation (logopedic massage, transcranial micropolarization). All sessions lasted 12 weeks, 3 times per week, 30–40 minutes each. Assessments included motor tests (Romberg, TUG, Box&Block, 9-Hole Peg Test, 10-Meter Walk Test, MotorSeq), speech parameters (articulation, vocabulary, comprehension), and ICF-based functional profiling.

Results. The intervention groups demonstrated significantly greater improvements compared to controls. Balance (Romberg test) improved by 54.4% vs 22.9% ($p<0.001$); gross motor coordination (MotorSeq) — by 19.7% vs 10.8% ($p<0.01$); finger dexterity (9-Hole Peg Test) — by 11.7% vs 4.4% ($p<0.001$). Speech articulation improved in 80% of children in the Briolight group vs 60% in controls ($p<0.001$); active vocabulary growth was observed in 90% vs 40% ($p<0.01$). The most pronounced differentiation was observed in Group 1 (fine motor focus — Box&Block, 9-Hole Peg, $p<0.05$–0.001), Group 2 (gross motor focus — TUG, 10MWT, MotorSeq, $p<0.001$), and Group 3 (speech — articulation, vocalization, imitation, $p<0.001$).

Conclusion. The Briolight interactive system provides a significantly higher and differentiated rehabilitation effect compared to standard methods, particularly in sensory-motor integration, speech activation, attention, and motivation. Its modular architecture enables individualized rehabilitation aligned with ICF-based functional profiles. The system is recommended for integration into multidisciplinary rehabilitation programs for children with PMSD, including those affected by war-related trauma.

Keywords: digital rehabilitation, children, psychomotor speech delay, interactive sensory system, ICF

PHOTODYNAMIC THERAPY WITH ZINC PHTHALOCYANINE RESULTS IN INCREASED LEVELS OF APOPTOSIS AND REDUCTION IN STEMNESS FEATURES OF MIA PACA-2 PANCREATIC CANCER CELL LINE

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Abstract
Pancreatic Cancer (PC) is a highly aggressive malignancy in the digestive system. Cancer stem cells (CSC) are considered to be the root of cancer recurrence, metastasis, and chemoresistance. The integration of laser technology and photomedicine continues to advance, offering new possibilities for cancer immunotherapy. Photodynamic therapy (PDT) may be particularly effective against CSCs resistant to traditional therapies. PDT is a minimally invasive and prospective cancer treatment method that consists of a photosensitive substance (PS) and a light source with a specific wavelength and produces reactive oxygen species (ROS), which oxidatively destroy cancer cells. In this regard, we aimed to investigate the survival rate, stemness features, and related gene expression following the implementation of PDT on the MIA PaCa-2 cell line. Initially, ZnPc-PDT was administered to PC cells, and in the subsequent phase, utilizing a methylthiazole tetrazolium kit (MTT assay), the cytotoxic effects of PDT on PC cells were examined. Using an ELISA reader, the optical density (OD) of each well was determined at a wavelength of 675 nm. The IC-50 dose was eventually determined. A flow cytometry test was performed to analyze the apoptosis. For this purpose, ZnPc-PDT pre-treated cells were stained by an annexin V FITC/PI kit. Furthermore, the expression of (Bcl2, caspase-9, -3) apoptosis-related genes and (SOX2, OCT4, Nanog) CSCs-related genes was evaluated in ZnPc-PDT pre-treated cells by Real-time PCR following extraction of cDNA. GraphPad Prism and Flowjo software analyzed the results. Our results indicated that implementation of ZnPc-PDT to PC cells increases apoptosis and the expression of pro-apoptotic genes (caspase-9, -3) in ZnPc-PDT treated cells after 48 hours of incubation compared to the untreated control group. These findings also brought attention to the cytotoxic effect of PDT on PC cells and revealed a significant reduction in CSCs-related genes and (Bcl2) antiapoptotic gene expression.

EFFECTS OF COGNITIVE BEHAVIOURAL INTERVENTION ON ANXIETY AMONG SENIOR SECONDARY SCHOOL STUDENTS IN CHIKUN LOCAL GOVERNMENT AREA OF KADUNA STATE, NIGERIA

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Abstract
This study investigated the effects of Cognitive Behavioural Intervention (CBI) on anxiety among male and female senior secondary school students in Chikun Local Government Area of Kaduna State, Nigeria. Specifically, the study evaluated the effectiveness of CBI in reducing anxiety symptoms among senior secondary school students and examined the effect of CBI on the anxiety levels of male and female senior secondary school students in Chikun Local Government Area. Two research questions guided the study, and two hypotheses were tested at the 0.05 level of significance. The study adopted a true experimental research design, specifically the pretest-posttest control group design. Forty-one senior secondary school students, comprising both male and female students, participated in the study, with 20 students assigned to the experimental group and 21 to the control group. Data were collected using a 9-item validated Anxiety Scale. The internal consistency of the instrument was established using Cronbach's alpha, which yielded a reliability coefficient of 0.943. Mean and standard deviation were used to answer the research questions, while Analysis of Covariance (ANCOVA) was used to test the hypotheses at the 0.05 level of significance. The findings revealed that CBI significantly reduced anxiety among students in the experimental group compared with those in the control group. The study concluded that CBI was effective in reducing anxiety among senior secondary school students. It was recommended that CBI be integrated into school-based counselling programmes in Kaduna State and that teachers and school counsellors be provided with training in basic cognitive behavioural techniques to support students experiencing anxiety.
Keywords: Cognitive Behavioural Intervention, Anxiety, Secondary School Students, Chikun Local Governt Area, Kaduna State, Nigeria

MOLECULAR, SEQUENCE AND PHYLOGENETIC ANALYSIS OF NEOSPOROSIS IN DOMESTIC PIGEONS IN KARBALA PROVINCE, IRAQ

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ABSTRACT
Neospora caninum is an obligate intracellular protozoan that infects warm-blooded animals that causes abortion and neonatal mortality in cattle and severe neuromuscular disease in dogs globally. The aim of this study was to evaluate the prevalence and risk factors of *N. caninum* infection in pigeons from Iraq and to perform molecular and sequence analyses of detected isolates. A total of 100 pigeons were examined for *Neospora* infection from January to April 2025using molecular analysis. with a total molecular prevalence of 9% (9/100). Sex was not significantly associated with infection rate. The genomic DNA that obtained a 334-bp fragment of the target sequence, was the first internal transcribed spacer (ITS1) of the rDNA (IQ1 gene for 18S rRNA, partial sequence. Comparisons of sequence revealed only one newly sequenced Iraqi isolates, but closely related genotypes at the same node with *Toxoplasma gondii* isolate. This finding suggests a potential common lineage or host- or geography-related similarity. The results of this study reflect that *N. caninum* is one of the parasitological agents confirmed in pigeons in Karbala province, Iraq.
Keywords: PCR, *Neospora caninum*, Pigeons, Iraq.

IN VIVO, IN VITRO, AND IN SILICO PHARMACOLOGICAL EFFECTS OF THE MEDICINAL SPECIES LOMELOSIA STELLATA L.

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Abstract
Rheumatoid arthritis is a chronic autoimmune inflammatory disease characterized by persistent joint inflammation, pain, and progressive joint damage. Despite available treatments, adverse effects and therapeutic limitations highlight the need for new anti-inflammatory agents. Consequently, there is a growing interest in medicinal plants as sources of novel therapeutic agents with fewer adverse effects than conventional drugs. In this study, we aimed to identify the chemical composition of the *n*-butanol (*n*-BuOH) extract of *Lomelosia stellata* and assess its *in vivo* pharmacological properties. Acute oral toxicity along with *in vivo* antipyretic and anti-inflammatory activities of the *n*-BuOH extract were tested on male albino Wistar rats using brewer's yeast-induced pyrexia and carrageenan-induced paw edema models. A new pentacyclic saponin named Lomelosin A (1), along with three known compounds (2-4), were isolated from the n-butanol extract of *Lomelosia stellata*. Their structures were identified through spectroscopic analysis (1H- and 13C-NMR, COSY, HSQC, TOCSY, NOESY and HMBC) and mass spectroscopy (HRESI-MS). Moreover, their molecular docking, pharmacokinetic and toxic parameters were studied. The results showed that all the isolated compounds had excellent binding affinity. The isolates exhibited potential toxicity, but they did not show any hepatotoxicity, mutagenicity or cytotoxicity. Moreover, the oral administration of the n-BuOH extract caused toxic symptoms associated with significant alterations in hematological and biochemical parameters. Histological examination of vital organs confirmed the observed toxicity. In addition, the administration of the *n*-BuOH extract significantly reduced acute paw edema and alleviated pyrexia. This work demonstrates that *L. stellata* species possesses remarkable anti-inflammatory and antipyretic effects *in vivo*. The combined structural elucidation, pharmacokinetic studies, and molecular docking suggest that the isolated compounds, particularly Lomelosin A, warrant further investigation as potential therapeutic agents.
Keywords: ADMET; *Lomelosia stellata*; molecular docking; NMR; saponins; antipyretic

INTEGRATING CANCER SCREENING INTO FAMILY PLANNING: LESSONS FROM EARLY-ONSET BREAST AND GYNECOLOGIC CANCERS IN NIGERIA

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ABSTRACT
Background: Early-onset breast, cervical, and ovarian cancers are rising among women of reproductive age (20-49 years) in Nigeria and West Africa, coinciding with peak contraceptive need. Family planning (FP) clinics are often the only routine contact young women have with the health system, yet cancer screening remains vertically siloed. This narrative review assessed prevalence, disparities, and opportunities for integrated cancer control within FP services.
Methods: We conducted a narrative review of literature from 2010-2025 using PubMed, AJOL, and Google Scholar. Search terms included early-onset, breast, cervical, ovarian cancer, Nigeria, West Africa, family planning, screening integration. We included 68 peer-reviewed articles, NDHS reports, and WHO/IARC data. Data were synthesized under four domains: prevalence, prevention, diagnosis/treatment disparities, and cancer control policy.
Results: Prevalence of early-onset breast cancer in Nigeria is 22-32% of all breast cancers vs <10% in high-income countries. Cervical cancer remains the second most common cancer in women aged 15-44, with screening coverage <15%. Key disparities identified: lack of awareness that hormonal contraceptives and nulliparity influence risk, limited clinical breast exam and HPV testing at FP clinics, stigma, cost, and weak referral linkage. Studies where Visual Inspection with Acetic Acid (VIA) and Clinical Breast Exam (CBE) were integrated into FP visits showed 2-3fold increase in screening uptake and improved continuation of contraception.
Conclusion & Program Implications: Integrating low-cost cancer screening (CBE, VIA/HPV self-sampling, ovarian cancer symptom awareness) into FP service delivery offers a high-impact, equitable platform for early detection in young women. Policy recommendation: strengthen FP providers' capacity, include cancer screening indicators in FP HMIS, and leverage domestic funding to sustain integrated reproductive health services aligned with FP2030 goals.
Keywords: Early-onset cancer, Family planning, Cervical screening, Breast cancer, Integration, West Africa

BREAST CANCER AND HARMFUL CHEMICAL & ENVIRONMENTAL EXPOSURES: THE ROLE OF CONSUMER PRODUCTS IN BREAST CANCER RISK

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ABSTRACT
Breast cancer is a major public health challenge worldwide, and growing evidence indicates that environmental exposures may contribute to breast carcinogenesis alongside established genetic, reproductive, and lifestyle-related factors. This narrative review explores the potential role of chemicals encountered through commonly used consumer products in breast cancer risk, with particular attention to endocrine-disrupting chemicals (EDCs) present in cosmetics, personal-care products, plastics, food packaging, household products, and pesticides. Evidence concerning bisphenols, phthalates, parabens, per- and polyfluoroalkyl substances (PFAS), and selected pesticides is examined, with emphasis on their potential biological effects and mechanisms of action. These chemicals may influence breast cancer development through disruption of hormonal signalling, oxidative stress, chronic inflammation, epigenetic modifications, DNA damage, altered cell proliferation, and impaired apoptosis. The review also considers the significance of exposure during critical developmental periods and the potential effects of repeated, low-level exposure to chemical mixtures. Particular attention is given to challenges in exposure assessment and the potential vulnerability of populations in low- and middle-income countries, where regulatory limitations, occupational exposures, informal markets, inadequate product labelling, and limited public awareness may increase exposure risks. Overall, the available evidence supports continued investigation of environmental chemical exposures as potentially modifiable contributors to breast cancer. Strengthening biomonitoring, chemical safety regulation, public education, and longitudinal research will be important for clarifying causal relationships and informing effective breast cancer prevention strategies.
Keywords: Breast Cancer, Consumer Products, Endocrine-Disrupting Chemicals, Environmental Exposure, Cancer Prevention

SMOKING CESSATION STRATEGIES IN CARDIOVASCULAR PREVENTION: A NARRATIVE REVIEW OF WORLD HEALTH ORGANIZATION GUIDELINES

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ABSTRACT

Objectives:
This narrative review aimed to synthesize the main recommendations of the World Health Organization (WHO) regarding smoking cessation support for adults, with particular attention to behavioral, pharmacological, digital, and healthcare-system interventions.

Methods:
A narrative review was conducted based on the WHO clinical guideline on tobacco cessation in adults, published in 2024. The guideline and related source documents were retrieved directly from the WHO IRIS platform. Recommendations were extracted and classified into four major intervention domains: behavioral support, pharmacological treatment, digital interventions, and healthcare-system organization.

Results:
The WHO recommends routinely offering brief tobacco cessation advice lasting 30 seconds to 3 minutes to all tobacco users during contact with healthcare professionals. More intensive behavioral support may be offered to individuals wishing to quit through individual or group counseling or telephone-based support. Recommended pharmacological options include varenicline, nicotine replacement therapy, and bupropion, while cytisine is also considered a therapeutic option. Combining a nicotine patch with a fast-acting nicotine formulation may be offered to users of nicotine replacement therapy. Digital interventions, including text messaging, mobile applications, artificial intelligence-based tools, and internet-based interventions, can complement cessation support. The WHO also recommends integrating smoking status and cessation interventions into medical records and strengthening healthcare professionals' training.

Conclusions:
WHO recommendations support an integrated approach to tobacco cessation combining brief advice, behavioral support, pharmacological treatment, and digital interventions. Integrating these strategies into primary care may strengthen tobacco control and contribute to cardiovascular disease prevention.

Keywords: Smoking cessation; Tobacco use; Cardiovascular prevention; WHO guidelines; Digital health

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AEROBIC-BASED CARDIAC REHABILITATION IMPROVES FUNCTIONAL CAPACITY AFTER CORONARY ARTERY BYPASS GRAFTING: A FOCUSED COMPARISON WITH CONVENTIONAL CARE

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Abstract
Functional recovery is a core goal of rehabilitation after coronary artery bypass grafting (CABG). The six-minute walk test (6MWT) is widely used because it is practical, prognostically meaningful, and closely related to real-world walking capacity. However, data from South Asia comparing exercise modalities after CABG remain limited.
To present a focused comparison of aerobic-based cardiac rehabilitation (Group A) versus conventional post-CABG care (Group A) on functional capacity measured by the 6MWT.
This paper reports a targeted two-group analysis from a two-arm randomized controlled trial involving 30 clinically stable post-CABG patients allocated equally to resistance-based rehabilitation, aerobic-based rehabilitation, or conventional care. The present comparison includes Group A and Group A. Functional capacity was assessed before and after a 10-week intervention. The parent trial analyzed post-intervention 6MWT distance with ANCOVA, using baseline 6MWT as a covariate.
At 10 weeks, unadjusted post-intervention 6MWT distance was 412.87 ± 13.86 m in Group A and 348.80 ± 31.12 m in Group B. After baseline adjustment, estimated marginal means were 409.89 m for Group A and 348.68 m for Group B. The adjusted mean difference was 61.21 m (95% CI 50.10 to 72.32; $p<0.001$). The group effect in the ANCOVA model was very large ($F=96.744$, $p<0.001$, partial $\eta^2=0.825$).
Aerobic-based cardiac rehabilitation produced a statistically robust and clinically meaningful improvement in post-CABG functional capacity compared with conventional care. The findings support aerobic-dominant training as a strong outpatient strategy for restoring walking ability after CABG.
Keywords: cardiac rehabilitation; CABG; aerobic training; six-minute walk test; functional capacity; physiotherapy

DIABETIC NEPHROPATHY AND ITS ASSOCIATED FACTORS AMONG HAEMODIALYSIS PATIENTS WITH DIABETES MELLITUS IN TRIPOLI, LIBYA: A HOSPITAL-BASED CROSS-SECTIONAL STUDY

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Abstract
Diabetic nephropathy is among the most clinically consequential microvascular complications of diabetes mellitus, and a primary driver of end-stage renal disease globally. Despite growing recognition of this burden, population-specific epidemiological data from Libya remain critically scarce, limiting the capacity of public health authorities to design evidence-based prevention and management strategies. To characterise the epidemiology of diabetes mellitus (DM) and its association with chronic kidney disease (CKD) among patients undergoing haemodialysis at Kidney Services Centre, Tripoli, Libya, with specific focus on glycaemic control, disease duration, co-morbid hypertension, and anthropometric status. A hospital-based, cross-sectional survey was conducted at the Haemodialysis Unit, Kidney Services Centre (KSC), Tripoli, between March and September 2020. Fifty patients with confirmed type 1 or type 2 DM were recruited using a structured, pre-validated questionnaire. Demographic characteristics, diabetes and hypertension duration, antidiabetic treatment regimen, body mass index (BMI), and glycated haemoglobin (HbA1c) were collected through direct patient interview and medical records review. Chi-square (χ^2) tests were used to assess associations between categorical variables, and Cox proportional hazards regression, adjusted for age and sex, was applied to estimate the independent contributions of key risk factors to renal outcomes. The cohort comprised 38 women (76%) and 12 men (24%), with a mean age of 52 ± 10 years. The 41–50-year age group constituted the largest proportion of patients (40%). Diabetes duration of two to five years was recorded in 52% of participants and was a statistically significant predictor of diabetic nephropathy (χ^2; $p = 0.01$). Co-morbid hypertension was present in 72% and independently associated with nephropathy ($p = 0.02$). The majority of patients (42%) exhibited severely uncontrolled glycaemia, with HbA1c exceeding 14%, and this subgroup demonstrated the strongest association with renal failure ($p = 0.01$). Oral antidiabetic agents constituted the most prevalent treatment modality (42%), followed by combined insulin–oral therapy (36%). The mean BMI was 22.1 ± 2.4 kg/m², with the majority falling within the normal weight range. Poorly controlled and long-standing diabetes mellitus, particularly in the presence of co-morbid hypertension, significantly amplifies CKD risk in this Libyan population. Urgent implementation of systematic screening programmes, multidisciplinary glycaemic management strategies, and early antihypertensive intervention is required to mitigate the expanding renal burden of diabetes in Tripoli and comparable settings across Libya.

Keywords: Diabetes Mellitus; Chronic Kidney Disease; Diabetic Nephropathy; HbA1c; Haemodialysis; Hypertension; Glycaemic Control; Prevalence; Tripoli; Libya

YAPAY ZEKÂ KULLANIMINI ETKİLEYEN UNSURLARIN ORTAYA KONMASI: BİR UYGULAMA††††††††††

DETERMINING THE FACTORS INFLUENCING THE USE OF ARTIFICIAL INTELLIGENCE: AN APPLICATION

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ÖZET
Yapay zekâ teknolojileri, son yıllarda yalnızca teknik uzmanlık alanlarında kullanılan sistemler olmaktan çıkarak gündelik yaşam, eğitim, medya, iletişim, iş süreçleri ve karar verme pratikleri içinde daha görünür hâle gelmiştir. Sohbet botları, öneri algoritmaları, içerik üretim araçları, görüntü ve ses tanıma sistemleri ile karar destek uygulamaları, bireylerin dijital ortamlarla kurduğu ilişkiyi yeniden biçimlendirmektedir. Bu dönüşüm, yapay zekânın yalnızca teknolojik bir gelişme olarak değil, aynı zamanda bireysel davranışları, toplumsal ilişkileri ve iletişim süreçlerini etkileyen çok boyutlu bir olgu olarak ele alınmasını gerekli kılmaktadır. Bu bağlamda bu çalışmada son zamanlarda hayatımızın vazgeçilmezi haline gelen ve gittikçe daha fazla kullanılan yapay zekâ araçlarının kullanım tercihlerini etkileyen unsurların ortaya konması amaçlanmıştır. İlk olarak araştırmacılar tarafından 32 ifadeden oluşan beşli Likert Tipinde bir ölçek geliştirilmiştir. Daha sonra kolayda örnekleme yöntemiyle belirlenmiş, çevrimiçi olarak ulaşılmış ve yapay zekâ araçlarını kullanan, 18 yaşından büyük toplam 612 kişiden veriler toplanmıştır. Verilere ilk olarak Açıklayıcı Faktör Analizi uygulanmıştır. AFA sonucunda örneklem büyüklüğünün yeterli olduğu görülmüştür. Verilerin faktör analizine uygunluğu teyit edildikten sonra ölçeğin faktör yapısının incelenmesi amacıyla Temel Bileşenler Analizi (Principal Components Analysis) ve Varimax Rotasyon yöntemleri kullanılarak açıklayıcı faktör analizi yapılmıştır. Açıklayıcı faktör analizi sırasında M10 ifadesi binişik değer aldığı için (iki yük değeri arasında 0.10 dan küçük) analizden çıkarılmıştır. Tekrarlanan AFA sonucunda beş faktörden oluşan toplam 31 maddelik ölçek ortaya konmuştur. Faktörler Eğlence ve Merak (6), Sosyal Etki ve Çevresel Faktörler (6), Mesleki Kaygı ve Gelecek Beklentisi (5), Algılanan Fayda ve Verimlilik (4), Güven ve Etik Değerler (5) ve Kullanım Kolaylığı (4) şeklinde adlandırılmıştır. Sonuç olarak geliştirilen ölçeğin bireylerin yapay zekâ araçlarını kullanma tercihlerini etkileyen altı faktörü ortaya koyduğu görülmüştür.
Anahtar Kelimeler: Yapay Zekâ, Yapay Zekâ Araçları, Yapay Zekâ Kullanımı

ABSTRACT
In recent years, artificial intelligence technologies have moved beyond being systems used only in technical fields and have become more visible in daily life, education, media, communication, business processes, and decision-making practices. Chatbots, recommendation algorithms, content creation tools, image and sound recognition systems, and decision support applications are reshaping the relationship individuals have with digital environments. This transformation necessitates that artificial intelligence be considered not only as a technological development but also as a multidimensional phenomenon affecting individual behaviors, social relationships, and communication processes. In this context, this study aims to reveal the factors influencing the usage preferences of artificial intelligence tools, which have recently become indispensable in our lives and are increasingly used. First, a five-point Likert-type scale consisting of 32 statements was developed by the researchers. Then, data was collected from a total of 612 individuals over the age of 18 who were selected using convenience sampling, accessed online, and used artificial intelligence tools. Exploratory Factor Analysis (EFA) was first applied to the data. The EFA results showed that the sample size was sufficient. After confirming the suitability of the

†††††††††† Bu çalışma, Sivas Cumhuriyet Üniversitesi Sosyal Bilimler Enstitüsü bünyesinde, Doç. Dr. İbrahim Yemez danışmanlığında Ferhat Yörük tarafından yürütülmekte olan *"Bireylerin Yapay Zekâ Kullanma Tercihlerini Etkileyen Faktörlerin İncelenmesi ve Çeşitli Faktörlere Göre Karşılaştırılması"* başlıklı yüksek lisans tez çalışmasından üretilmiştir.

data for factor analysis, exploratory factor analysis was performed using Principal Components Analysis (PCA) and Varimax Rotation methods to examine the factor structure of the scale. During the exploratory factor analysis, the M10 expression was excluded from the analysis because it had an overlapping value (less than 0.10 between two loading values). The repeated EFA results in a 31-item scale consisting of five factors. The factors were named as Entertainment and Curiosity (6), Social Influence and Environmental Factors (6), Occupational Anxiety and Future Expectations (5), Perceived Benefit and Productivity (4), Trust and Ethical Values (5), and Ease of Use (4). In conclusion, the developed scale was found to reveal five factors influencing individuals' preferences for using artificial intelligence tools.
Keywords: Artificial Intelligence, Artificial Intelligence Tools, Use of Artificial Intelligence

GİRİŞ

Yapay zekâ, insan zekâsıyla ilişkilendirilen öğrenme, akıl yürütme, problem çözme, karar verme, dil anlama ve örüntü tanıma gibi işlevlerin bilgisayar sistemleri tarafından yerine getirilmesini amaçlayan teknoloji alanı olarak tanımlanabilir (Russell ve Norvig, 2021). Yapay zekâ, multidisipliner bir bakış açısıyla makinelerin insan gibi düşünme yetileri kazanmasını mümkün kılarak, çeşitli süreçler ve problemler karşısında çözümler üretebilmesini amaçlamaktadır (Öymen, 2021). Başka bir ifadeyle yapay zekâ temelde insanın bilişsel süreçlerini taklit eden, çevreden edindiği verilere dayanarak uyumlu tepkiler veren ve bu konuda karar alan yapay bir olgu şeklinde tanımlanabilir (Jarrahi, 2018). Sahip olduğu bu özellikler ile yapay zeka uygulamalarının insanların günlük hayatta yaptığı birçok şeyi daha hızlı ve daha kolay yapabilme yeteneği, bu uygulamaların her geçen gün daha fazla sayıda kullanıcıya ulaşmasını ve kullanım alanının da sürekli olarak genişlemesine imkan verdiği söylenebilir.

Yapay zekâ teknolojileri, son yıllarda yalnızca teknik uzmanlık alanlarında kullanılan sistemler olmaktan çıkarak gündelik yaşam, eğitim, medya, iletişim, iş süreçleri ve karar verme pratikleri içinde daha görünür hâle gelmiştir. Sohbet botları, öneri algoritmaları, içerik üretim araçları, görüntü ve ses tanıma sistemleri ile karar destek uygulamaları, bireylerin dijital ortamlarla kurduğu ilişkiyi yeniden biçimlendirmektedir. Bu dönüşüm, yapay zekânın yalnızca teknolojik bir gelişme olarak değil, aynı zamanda bireysel davranışları, toplumsal ilişkileri ve iletişim süreçlerini etkileyen çok boyutlu bir olgu olarak ele alınmasını gerekli kılmaktadır.

Yeni medya ve iletişim alanı açısından yapay zekâ, kullanıcıların bilgiye ulaşma, içerik üretme, medya tüketme ve dijital platformlarla etkileşim kurma biçimlerini doğrudan etkileyen teknolojilerden biridir. Algoritmik öneri sistemleri, kişiselleştirilmiş içerikler, otomatik metin üretimi, görsel tasarım araçları ve sohbet temelli uygulamalar, bireylerin hem kullanıcı hem de üretici konumunu dönüştürmektedir. Bu nedenle yapay zekâ kullanımını incelemek, yalnızca araçların teknik özelliklerini açıklamakla sınırlı değildir; kullanıcıların bu teknolojilere neden yöneldiğini, hangi koşullarda benimsediğini ve hangi kaygılarla mesafeli durduğunu anlamayı da gerektirir.

Bireylerin yeni teknolojileri benimseme süreçleri, literatürde çoğunlukla algılanan fayda, algılanan kullanım kolaylığı, sosyal etki, güven, risk algısı ve kullanım niyeti gibi değişkenler üzerinden açıklanmaktadır. Teknoloji Kabul Modeli, bireylerin bir teknolojiyi kullanma eğiliminde algılanan fayda ve algılanan kullanım kolaylığının belirleyici olabileceğini öne sürmektedir (Davis, 1989). Birleştirilmiş Teknoloji Kabul ve Kullanım Teorisi ise performans beklentisi, çaba beklentisi, sosyal etki ve kolaylaştırıcı koşulların teknoloji kullanım niyeti üzerinde etkili olabileceğini belirtmektedir (Venkatesh vd., 2003). Bu yaklaşımlar, yapay zekâ araçlarının bireyler tarafından nasıl değerlendirildiğini açıklamak için önemli bir kuramsal zemin sunmaktadır. Bu bağlamda bu çalışmada bireylerin yapay zekâ kullanımını etkileyen faktörlerin ortaya konması amaçlanmıştır.

METODOLOJİ

Araştırmanın Amacı

Bu çalışmada bireylerin yapay zeka kullanımını etkileyen faktörlerin saptanması ve ortaya konması amaçlanmıştır. Bu anlamdan araştırmacılar tarafından beşli Likert tipinde bir ölçek geliştirilmiş ve bu ölçeğin yapısı ve iç tutarlılığı ortaya konulmuştur.

Araştırmanın Evreni ve Örneklemi

Araştırmanın evrenini Türkiye'de bulunan ve yapay zeka kullanan bireyler oluştururken, örneklem ise kolayda örnekleme yöntemiyle seçilen, 18 yaş üstü ve çevrimiçi erişim sağlanan toplam 612 kişiden oluşmaktadır. Araştırmada zaman ve maliyet sınırlamaları nedeniyle çevrimiçi anket yoluyla veriler elde edilmiştir. Araştırmada eksik veya hatalı veri bulunmadığı için tüm analizler 612 kişilik veri ile yapılmıştır.

Araştırmanın Veri Toplama Aracı

Araştırmada Beşli Likert Tipinde (1-Kesinlikle Katılmıyorum, ... ,5-Kesinlikle Katılıyorum) toplam 32 ifadeden oluşan ölçek kullanılarak bireylerin yapay zekâ uygulamalarını kullanma tercihlerini etkileyen faktörler anket yöntemiyle ölçülmüştür. Ölçüm aracındaki tüm ifadeler araştırmacılar tarafından oluşturulmuştur. Ayrıca ankette demografik sorular da yer almaktadır.

Kullanılan İstatistiksel Analizler

İlk aşamada Frekans analizi yapılarak demografik bulgular tanımlanmıştır. Daha sonra Açıklayıcı Faktör Analizi yapılarak bireylerin yapay zekâ araçlarını kullanma tutumlarını etkileyen faktörler ortaya konmuştur. Son aşamada ise Cronbach Alpha ile faktörlerin iç tutarlılığı ortaya konarak ölçeğin güvenilir olduğu ortaya konmuştur.

BULGULAR VE TARTIŞMA

Demografik Bulgular

Çalışmaya katılanların %38,1'i kadın, %61,9'u ise erkektir. Medeni duruma göre katılımcıların %21,1'i evli, %78,9'u ise bekârdır. Yaş dağılımına göre en yüksek katılım %66,8 ile 18-24 yaş arası gençlerdeyken, en az katılım ise %0,5 ile 60 yaş ve üzeri katılımcılardadır. Eğitim durumuna göre en yüksek katılım %43,6 ile lisans mezunlardayken, en az katılım ise %4,1 ile lisansüstü mezunu kişilerdedir. Aylık ortalama gelire göre en yüksek katılım %61,4 ile 30000 TL ve altı geliri olanlardayken, en az katılım ise %5,9 ile 375001-45000 TL ve 45001-52500 TL geliri olanlardadır. Son olarak mesleğe göre en yüksek katılım %40,8 ile öğrencilerdeyken, en az katılım ise %5,6 ile tüccar/esnaflar grubundaki çalışanlardadır.

Açıklayıcı Faktör Analizine İlişkin Bulgular

Verilerin faktör analizine uygun olup olmadığı ilk olarak kontrol edilmiştir. Bu amaçla KMO değeri 0,948 olarak hesaplanmış ve örneklem yeterliliğinin çok iyi olduğu tespit edilmiştir. Barlett küresellik testi sonucunda Ki-Kare Değeri: 11795,273; $p=0.000<0.05$ olduğundan taslak ölçeğin AFA'ya uygun olduğu belirlenmiştir. Faktör analizine uygunluk onaylandıktan sonra ölçeğin faktör yapısını belirlemek amacıyla Temel Bileşenler Analizi ve Varimax Rotasyonu teknikleriyle AFA gerçekleştirilmiştir. Verilerin faktör analizine uygunluğunun doğrulanmasının ardından ölçeğin faktör yapısının araştırılması için Temel Bileşenler Analizi ve Varimax Rotasyon yöntemleriyle açıklayıcı faktör analizi gerçekleştirilmiştir. Açıklayıcı faktör analizi esnasında M10 ifadesi binişik değer aldığı için (iki yük değeri 0.10'dan küçük) analizin dışında bırakılmış ve tekrar edilmiştir. 31 maddenin tümü ile yapılan AFA sonucunda elde edilen faktörler ve bu faktörlerin altında yer alan maddelere ilişkin faktör skorlarını içeren döndürülmüş bileşenler matrisi, özdeğer, varyans ve kümülatif varyans değerleri Tablo 1'de gösterildiği şekilde belirlenmiştir.

Tablo 1. Döndürme Sonrası Faktörler ve Madde Yük Değerleri

Maddeler	1	2	3	4	5	6
M23	,779					
M24	,760					
M25	,748					
M22	,743					
M26	,653					
M27	,600					
M17		,702				
M19		,664				
M21		,653				
M20		,626				
M16		,621				
M18		,616				
M29			,817			
M32			,779			
M30			,730			
M31			,489			
M28			,402			
M3				,775		
M2				,728		
M4				,724		
M5				,681		
M1				,641		
M12					,762	
M14					,730	
M13					,703	
M15					,654	
M11					,629	
M7						,792
M8						,779
M6						,690
M9						,561

Tablo 1'de bulunan ölçeğin faktör analizi sonuçları incelendiğinde, döndürme sonrası maddelerin toplam 6 faktörde toplandığı ve maddelerin faktör yükü değerlerinin 0.402 ile 0.817 arasında değişiklik gösterdiği gözlemlenmektedir. Maddelerin bağlı olduğu faktörle ilişkisini ifade eden faktör yük değeri katsayısı için uygulamalarda genellikle 0.45'tan yüksek değerler madde seçimi açısından uygun bir kriter olarak önerilmektedir (Büyüköztürk, 2002: 118). Ayrıca Tablo 1'e dayanarak Varimax rotasyonu ile elde edilen faktör yüklerinin, 1 madde için 0.32-0.44 arasında "kötü", 1 madde için 0.45-0.54 arasında "normal", 6 madde için 0.55-0.62 arasında "iyi", 7 madde için 0.63-0.70 arasında "çok iyi" ve 16 madde için 0.71 ve üzeri "mükemmel" seviyelerinde dağıldığı gözlemlenmektedir.

Elde edilen faktörlere dair diğer sonuçlar Tablo 2'de yer almaktadır. Tablo 2'de bulunan 6 faktörün öz değerlerinin 1'den fazla olduğu gözlemlenmektedir. Genellikle ölçeğe dâhil edilecek faktör sayısını tespit ederken özdeğeri 1'den büyük olan faktörler dikkate alınmaktadır (Büyüköztürk, 2002: 119). Bu altı faktörün açıkladığı varyanslar %8 ile %14 arasında değişmekte olup, toplam açıklanan varyans %65,367 olarak gözlemlenmektedir. Bu verilere dayanarak yapılan analizde, ortaya çıkan altı faktörün toplam yapının varyansının yaklaşık %65'ini açıkladığı tespit edilmiştir. Bu değer Kline'a göre %40'tan fazla olduğu için kabul edilebilir bir seviyededir (Ceyhan ve Namlu, 2000: 77-93). Hesaplanan toplam açıklanan varyans yaklaşık % 65 olup, bu değerin üzerinde bir değerdir ve tatmin edici olarak değerlendirilebilir.

Tablo 2. Faktör Yükleri, Öz Değerler ve Kümülatif Varyans

Ölçek Alt Boyutu	Maddeler	Fak. Yükleri	Özdeğer	Varyans (%)	Kümülatif Var. (%)
Faktör 1	M23	,779	12,685	14,187	14,187
	M24	,760			
	M25	,748			
	M22	,743			
	M26	,653			
	M27	,600			
Faktör 2	M17	,702	2,754	11,883	26,070
	M19	,664			
	M21	,653			
	M20	,626			
	M16	,621			
	M18	,616			
Faktör 3	M29	,817	1,720	10,985	37,055
	M32	,779			
	M30	,730			
	M31	,489			
	M28	,402			
Faktör 4	M3	,775	1,402	10,904	47,959
	M2	,728			
	M4	,724			
	M5	,681			
	M1	,641			
Faktör 5	M12	,762	1,337	8,892	56,851
	M14	,730			
	M13	,703			
	M15	,654			
	M11	,629			
Faktör 6	M7	,792	1,019	8,516	65,367
	M8	,779			
	M6	,690			
	M9	,561			

Faktörlerin Adlandırılması

Genel olarak faktör analizinin amacı, birçok değişkeni daha az sayıda değişkene dönüştürmek olduğundan, bu indirgemeye dayanan değişkenlere isim verilmesi gerekmektedir. Bu isimlendirme işlemi, faktörü oluşturan değişkenlerin yapısına dayalı olarak da gerçekleştirilebilir (Nakip, 2013: 524). Bu çerçevede faktörlerdeki unsurların ifade ettikleri anlamlar dikkate alınarak faktörler şu şekilde isimlendirilmiştir.

Faktör 1: Eğlence ve Merak
Faktör 2: Sosyal Etki ve Çevresel Faktörler
Faktör 3: Mesleki Kaygı ve Gelecek Beklentisi
Faktör 4: Algılanan Fayda ve Verimlilik
Faktör 5: Güven ve Etik Değerler
Faktör 6: Kullanım Kolaylığı

Güvenirlik Bulguları

Altı faktör ve 31 maddeden oluşan ölçeğe ait Cronbach α değerleri aşağıdaki Tablo 3'de verilmiştir.

Tablo 3. Ölçek Güvenirlik Katsayıları

Faktörler	Cronbach α
Faktör 1: Eğlence ve Merak	**0,918**
Faktör 2: Sosyal Etki ve Çevresel Faktörler	**0,892**
Faktör 3: Mesleki Kaygı ve Gelecek Beklentisi	**0,847**
Faktör 4: Algılanan Fayda ve Verimlilik	**0,841**
Faktör 5: Güven ve Etik Değerler	**0,796**
Faktör 6: Kullanım Kolaylığı	**0,817**

İç tutarlılığı değerlendirmek için kullanılan Cronbach α katsayısının 0,60-0,79 arasında olması, ölçeğin "oldukça güvenilir"; 0,80-1,00 aralığında olması ise ölçeğin "yüksek güvenilirlikte" olduğunu ifade etmektedir (Tavşancıl, 2014: 29). Tablo 3'e göre Güven ve Etik Değerler faktörünün değeri 0,700'den fazla olduğu için oldukça güvenilir; diğer beş faktör ise 0,800'den büyük olduğu için yüksek bir güvenirlik sergilediği tespit edilmiştir. Böylece Türkçe'ye kazandırılan ölçeğin güvenilirliği belirlenmiştir.

SONUÇ VE ÖNERİLER

Günümüzde yapay zekâ araçları, bireylerin bilgi arama, öğrenme, yazma, üretme, planlama, karar alma ve iletişim kurma süreçlerinde giderek daha fazla kullanılmaktadır. Ancak bu teknolojilerin yaygınlaşması, bütün kullanıcıların yapay zekâ araçlarını aynı düzeyde, aynı amaçlarla veya aynı gerekçelerle benimsediği anlamına gelmemektedir. Bu nedenle bireylerin yapay zekâya yönelik kullanım tercihlerini belirleyen unsurların açıklanması hem kullanıcı davranışlarının hem de dijital iletişim süreçlerinin anlaşılması açısından önem taşımaktadır.

Araştırma, yapay zekâ kullanımını yalnızca teknik bir erişim veya beceri meselesi olarak ele almamaktadır. Bunun yerine, bireylerin yapay zekâ araçlarına yönelik algılarını, beklentilerini, çekincelerini ve kullanım motivasyonlarını birlikte değerlendirmektedir. Bu çerçevede algılanan kullanım kolaylığı, algılanan fayda, güvenlik algısı, mahremiyet ve veri koruma kaygısı, etik değerler, sosyal faktörler, merak, yenilikçilik eğilimi ve mesleki nedenler araştırmanın temel inceleme alanlarını oluşturmaktadır. Böylece çalışma, yapay zekâ kullanım tercihlerinin tek bir değişkenle açıklanamayacak kadar çok boyutlu bir yapıya sahip olduğu varsayımından hareket etmektedir.

Yeni medya ortamlarında yapay zekâ araçlarının artan görünürlüğü, araştırmanın konusunu daha da önemli hâle getirmektedir. Sosyal medya platformları, arama motorları, çevrim içi içerik üretim araçları, sohbet botları ve algoritmik öneri sistemleri, bireylerin dijital deneyimlerinin önemli bir parçası hâline gelmiştir. Bu araçlar, kullanıcıların yalnızca neye eriştiğini değil, aynı zamanda neyi nasıl ürettiğini, hangi içeriğe yöneldiğini ve dijital ortamda nasıl davrandığını da etkileyebilmektedir. Bu nedenle yapay zekâ kullanım tercihleri, yeni medya ve iletişim çalışmaları bakımından kullanıcı, teknoloji ve toplumsal bağlam arasındaki ilişkiyi değerlendirmeye imkân veren bir araştırma alanı sunmaktadır. Bu bağlamda bu araştırmada bireylerin yapay zekâ uygulamalarını kullanma tercihlerini etkileyen faktörler ortaya konulmak istenmiştir. Çalışmada araştırmacılar tarafından geliştirilen ve 32 ifadeden oluşan ölçek 612 kişiden veriler toplanarak Açıklayıcı Faktör Analizine tabi tutulmuştur. AFA sonucunda 6 boyuttan ve 31 maddeden oluşan taslak ölçek ortaya çıkmıştır. Faktörler *Algılanan Fayda ve Verimlilik, Kullanım Kolaylığı, Güven ve Etik Değerler, Sosyal Etki ve Çevresel Faktörler, Eğlence ve Merak ve Mesleki Kaygı ve Gelecek Beklentisi* şeklinde adlandırılmıştır. Faktörlerin madde yük değerleri ve iç tutarlılık katsayıları istenen kriterleri taşıdığı için taslak ölçek bu haliyle kabul edilmiştir. Çalışma sonucunda geliştirilen ölçeğin bireylerin yapay zekâ uygulamalarını etkileyen faktörleri ortaya koyan bir ölçek olduğu ve bundan sonraki çalışmalarda kullanılabileceği ortaya konmuştur.

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INTERMEDIATE WHEATGRASS (*THINOPYRUM INTERMEDIUM*) AS A MODEL FOR INNOVATION IN PERENNIAL GRAIN BREEDING: FROM CONVENTIONAL SELECTION TO GENOMICS-ASSISTED AND MACHINE LEARNING APPROACHES

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Abstract
Perennial cereal crops offer a potential alternative for mitigating the adverse effects on soil and the environment caused by annual cereal production. Among these species, *Thinopyrum intermedium* (intermediate wheatgrass) has become one of the species that comes closest to commercial perennial cereal production, particularly thanks to breeding efforts aimed at developing Kernza®. The transformation of *T. intermedium*—initially evaluated as a forage crop and for soil conservation—into a perennial cereal crop over a breeding programme spanning approximately ten generations represents a significant example of progress in breeding methods. This mini-review covers this development, from early-stage phenotypic selection through to genomic selection via molecular markers, QTL mapping and genome-wide association studies (GWAS), and on to the emerging machine learning-supported high-throughput phenotyping approaches. In early-stage breeding studies, phenotypic selection was applied to fundamental domestication traits such as grain yield, grain weight, reduced shattering, and characteristics of bare and easily threshed grains. Subsequent molecular and genomic studies have contributed to the identification of the genetic architecture of these traits and the associated QTL regions, whilst genomic selection has begun to be utilized to shorten breeding cycles and select superior genotypes at earlier stages. In addition, the review addresses emerging applications of approaches such as machine learning and image-based root phenotyping in T. intermedium, although these are still limited. The review also discusses agronomic and environmental aspects of the species, such as its perennial root system, reduced tillage requirements, potential benefits in terms of soil and water resources, and its suitability for use as grain and fodder. Finally, ongoing breeding challenges and yield limitations are addressed with a view to enhancing the competitiveness of perennial cereals against existing annual cereals.
Keywords: Intermediate wheatgrass, Perennial grain crops, Genomic selection, Molecular markers, Machine learning, Plant breeding innovation

Introduction
Global agriculture faces significant challenges associated with annual cereal production, arising from practices such as leaving the soil bare after harvest, shallow root systems and repeated tillage. These practices can contribute to soil erosion, carbon loss and a reduction in water-holding capacity. Perennial cereal crops, however, offer an alternative approach to these problems. The preservation of living root systems within the soil throughout the year can contribute to soil stabilisation, an increase in soil organic matter, improved water-holding capacity and a potential reduction in the inputs required in traditional annual farming systems (Singh, 2025; Kantar et al., 2016). Among the perennial cereal candidates developed for these purposes, *Thinopyrum intermedium* has become one of the species that has made

the most progress towards commercial cereal production, particularly thanks to the breeding work carried out under the Kernza programme (DeHaan et al., 2018).

Unlike major annual cereal crops such as wheat, rice and maize, *Thinopyrum intermedium* has not historically been domesticated as a cereal crop. The transformation of this species from a grass used for fodder and soil conservation into a perennial cereal crop took place over just a few decades and a breeding process spanning approximately ten generations (Ravetta et al., 2025; Crain et al., 2024). Therefore, *T. intermedium* serves as an important case study for examining the development of breeding strategies. Whilst early development efforts relied on selection based on observable agronomic traits, subsequent studies have incorporated molecular and genomic approaches such as marker-assisted selection, QTL analysis, GWAS and genomic selection (Zhang et al., 2022; Crain et al., 2021; Crain et al., 2020). With the recent emergence of artificial intelligence and machine learning tools in plant breeding, these technologies also offer new opportunities to accelerate the breeding process for *T. intermedium*. The fact that the species is still at a relatively early stage of product development means that its recent breeding history provides a clear example of the transition from traditional selection to modern genomics-assisted and emerging artificial intelligence-assisted breeding approaches.

The purpose of this review is to use intermediate wheatgrass as a case study for how breeding methodology is evolving in perennial crop development — from phenotype-based selection toward genomic and AI-assisted approaches — and to assess what this shift means for the crop's path toward agronomic competitiveness. Drawing on published agronomic, breeding, and genetic diversity literature, it traces this progression and identifies the obstacles that remain before intermediate wheatgrass can compete with established annual grains.

Agricultural and Environmental Value

Intermediate wheatgrass (*Thinopyrum intermedium*) is a perennial plant which, unlike annual cereal crops, does not need to be replanted every year. Its perennial root system maintains its viability in the soil throughout the plant’s growing seasons, providing continuous ground cover and contributing to nutrient retention and other ecosystem services (Law et al., 2022; Jungers et al., 2019). Furthermore, field studies have shown that IWG cultivation is associated with lower nitrate leaching compared to annual wheat, highlighting the potential environmental benefits of perennial grain production (Reilly et al., 2022).

In addition to grain production, the fact that IWG can also be harvested for fodder makes this species a potential dual-purpose crop for integrated cereal-livestock systems (Law et al., 2022). These characteristics have increased interest in the development of IWG as a perennial grain crop. However, its perennial growth habit also presents certain challenges in maintaining grain yield during the breeding process and across successive production years.

Breeding Process: From Conventional Breeding to AI-Supported Breeding Approaches

Breeding of intermediate wheatgrass (*Thinopyrum intermedium*) for perennial grain production was initially carried out using conventional phenotypic selection methods. In the early domestication studies, large field populations were evaluated and superior individuals were selected for traits such as grain yield, grain weight, reduced shattering, increased proportion of naked or freely threshable grains, fertility and plant architecture. The breeding programme at The Land Institute has refined these strategies over successive selection cycles and has demonstrated that significant predicted genetic gains have been achieved in key domestication traits such as grain yield, the proportion of naked grains and grain weight (DeHaan et al., 2018).

The perennial and predominantly outcrossing biology of *T. intermedium* poses a significant challenge for rapid breeding. Prior to the implementation of genomic selection, selection cycles typically required approximately 2–5 years, which significantly prolonged the time needed to evaluate and re-cross superior genotypes (Crain et al., 2021). The characteristics of outcrossing and self-incompatibility necessitate the careful management of hybridization and mating populations. In subsequent periods, genomic approaches have been utilized to determine parental relationships within breeding populations and to optimize polycrossing systems (Bajgain et al., 2022).

The development of molecular markers has marked a significant step in the transition from breeding methods based solely on phenotypic selection to genomic-assisted breeding approaches. The

characterization of 193 populations of *T. intermedium* using AFLP markers revealed a high level of genetic variation and differentiation; it was determined that 31 per cent of the molecular variation occurred between populations and that genetic groupings were generally associated with Asian and European origins (Jensen et al., 2016). Subsequent SNP- and genotyping-by-sequencing (GBS)-based studies have enabled QTL mapping and genome-wide association studies (GWAS) to be conducted with the aim of identifying the genetic basis of domestication traits such as grain size, grain shattering, combinability, flowering, fertility and yield. For example, QTL mapping studies identified a total of 111 QTLs across 36 genomic regions for traits associated with grain production; subsequent analyses encompassing multiple selection cycles identified numerous marker-trait associations and demonstrated that key domestication traits are largely polygenic in nature (Larson et al., 2019; Crain et al., 2022). Whilst these results provide potential targets for marker-assisted selection, they also highlight why genome-wide approaches are particularly valuable in managing such complex traits.

Genomic selection has since become a key component of the IWG breeding programme. Zhang et al. (2016) evaluated various genomic prediction models, including Random Forest, with the aim of accelerating the domestication process; Crain et al. (2021), meanwhile, demonstrated that this approach could be applied in practice within the IWG breeding programme. With the introduction of genomic selection in 2017, the breeding cycle has been reduced from approximately 2–5 years to approximately one year, thanks to the calculation of genomic prediction selection values prior to comprehensive field evaluations using genotyping by sequencing (GBS) data. Predicted genetic gains of approximately 6–14 per cent per year have been reported for many priority traits, such as ear yield, grain weight, free thresh-ability and resistance to grain shattering (Zhang et al., 2016; Crain et al., 2021).

More recently, machine learning approaches have begun to extend genomics-assisted breeding towards high-throughput phenotyping applications. In *T. intermedium*, Griffin et al. (2025) developed a platform combining minirizotron imaging and machine learning software to quantitatively characterize root traits. The study highlights the potential of machine learning for high-throughput phenotyping in IWG and provides a basis for its future integration with genomic selection approaches. Consequently, the breeding process for *T. intermedium* can be viewed as a progression from intensive phenotypic selection to molecular marker and QTL/GWAS approaches, followed by genomic selection and increasingly advanced machine learning-supported phenotyping applications (Figure 1).

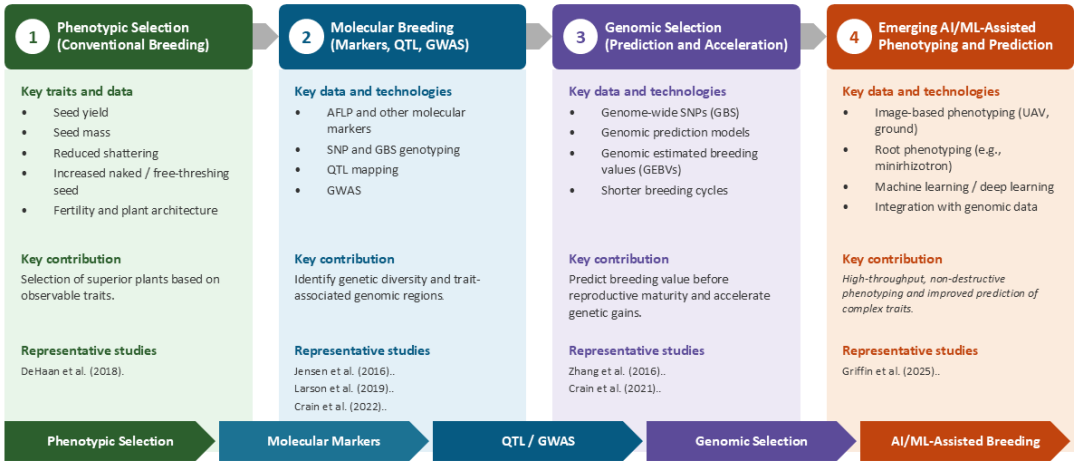


Figure 1. Overview of the progression from conventional phenotypic selection to molecular marker-assisted breeding, genomic selection, and emerging AI/ML-assisted approaches for crop improvement.

Conclusion and Recommendations

Intermediate wheatgrass (*Thinopyrum intermedium*) provides a clear example of the transition from conventional selection to genomics-assisted approaches in the breeding of perennial plants. Whilst early breeding studies highlighted the importance of phenotypic selection for domestication traits such as grain yield, grain weight, thresh-ability and resistance to shattering, subsequent molecular marker studies have provided a better understanding of genetic diversity and the genetic basis of these traits.

The application of genomic selection has represented a significant advance by substantially shortening breeding cycles and enabling the selection of superior genotypes at earlier stages. More recently, the introduction of machine learning approaches for high-throughput phenotyping has further expanded the scope of the technological tools available for IWG breeding. Overall, the breeding history of IWG demonstrates that the integration of phenotypic assessments with molecular, genomic and computational approaches can support faster and more targeted genetic progress. The development and combined use of these approaches are crucial for improving the agronomic performance of IWG and transforming it into a more competitive perennial grain crop.

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FROM YOUTH'S MIND

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Abstract
The need of a youth to be able to agree and decide on his own, Some, of the young children choose or do thing according to the need of their parents and hence they lose their own right of making their own choice in some ways we all know that they are being denied their freedom of speech which even in the constitution of India, Article 19 clause "a" it also says that each person has a freedom of speech and expression. So, this means even youth have the right to that Article, but because the youth are not able to express their felling on what they want they then decide to do something that their parents, friend or relatives decide for them. So, this is to tell the youth that they need to make their decision but ask for advice so they can know how to do it better.
Keywords: Freedom of speech and expression,

1. INTRODUCTION

In life everything that we do it is because we wish to do it and sometimes it's because we have an influencer to tell us what we want and what we wish for but we forget to use our own mind and knowledge on what we want to do because we are young. But we also think that because we are young we can't make our own decisions and then we make thoughts that we need an adult into making our decisions but in realty adults are just there to advice and guide us on what we do so as we can be able to know what is right for our future and what is not right to our future. They also help us to know what we want and hence they make us be able to archive our goals buy supporting us.

1.1 How to understand yourself

- **Meditation**

This helps a person to be able to understand himself/ herself, you can take a day to meditate and understand your goals and know what how to manage your abilities in the things you what to achieve

- **Keep your own journaling**

This means to write down your thoughts and feeling so as you can be able to understand yourself in a detailed way.
It also helps with mental health, because if you are not arranged and well planed it can make you feel exhausted or not having clear thought on what you plan to do next and hence it may lead to stress and depression which may disturb your mental health
But also journaling helps to keep thing in a memorial way because we all know that if you want to improve something you have to write and practice hence it will be well memorized
It can also help emotionally because some people tend to write or not down anything they want when they are in an emotional state, hence this act of journaling can also help easy the emotional state and make you be able to select or think of what you want to be and note it down

- **Questioning yourself**

In this aspect you have to ask yourself different questions and then apply these question in your daily life and get the answers. In real life and specific areas is were your answers can be obtained and they can be obtained in a positive way or a negative way and that is when you can realize if you are right in that aspect you wanted or you are not in the aspect you wanted

QUESTIONS TO ASK YOURSELF

✓ What are the reasons that made you want to do what you are doing at this time?

- ✓ What is the important of that thing in your life?
- ✓ Who/how will your career help you and the society?
- ✓ Are you sure your career will help the society?
- ✓ If you get your career what will you do after you have achieved it?
- ✓ If you archive your career will you real use it to help the society or benefit it yourself?

- Know your weakness

Sometimes you have to know what is your weakness so as you can be able to do something in away that it will not affect you either in any kind of situation which can be either emotional , psychically, and mentally because sometimes the things that cause problem are the weakness we have in our life that we cant overcome hence they can push us back and we can not be able to know what career or what thing can we be able to do which is the one we can't do.

- **BELIVING IN YOURSELF.**

This is an act were a youth has to keep and know his/her trust, confidence, worth and also know his/herself environment abilities .This is because if you won't trust yourself then it will be hard for you to reach your goal but if you are able to have faith and believe yourself in anything then you will be able to do anything good for yourself.

Because some people tell their parent to tell them their career while in reality they should be able to know what they need though their own trust and believes are not on there shoulders but their in their parents hand this is because they know their parent will identify their career because they saw what they have in them since childhood. But some are able to believe and trust them selves and this helps them to identify their own abilities in different activities they want to do because of confidence which was brought by self believing and trust .

- ✓ In this part of believing this is when we meet some young youth who have straggled and have archive their own goals just in their early 20's this is because of believing in themselves and it is also because they had self determination on reaching at that particular point they are at this particular moment.

- **DETERMINATION.**

This is act were a person real intends on doing something with his/her own strength without hesitation. Young youth who are mostly succeed at their 20's its because they had determination of doing that particular thing and they struggled without giving up on hope so as they could archive what they have to day.

- ✓ **In order a person to understand him/herself has to be able to know everything about him/herself hence what he/she needs in his/her life and it will be easy for the person to know which way will be right for him/her in future.**

1.2. HOW TO KNOW YOUR CAREER / FUTURE.

In order to know your career/ future you have to start by understanding your strengths interests and values.

A person needs the following to be able to know his/her career / future

- **IDENTIFY YOUR STRENGTH.**

This means the ability to do something on your own with all strength / power that you have then this will mean that you are ready to do such thing and you are capable to such thing

- **HAVING INTEREST**

You must have or know your interest on a particular thing that you want to do or you want to have because if you have interest in thing you do it means that you will do them with all your heart and strength. In interest you must also do something that you like to enjoy so as you can be able to do it with all your effort because you love it.

- **VALUE SHOULD BE DEFINE**

In the value of you future/ career you must know how important is your job. In the important of value you must look at the work life balance, salary and impacts of the job or career that you want to do in the future of your life.

In the career / future of life a person must be ready to also choose career/ future their different problems that a person can pass through and lose hope because of the problem or reasons a person can pass through while trying to understand your own career/ future.

The following are problem that can occur and make someone not be able to understand his / her career/ future.

- **FEAR**

Sometimes fear can also be a problem because a person can be worried about how he/ she will work on different arear. Example a person can have fear to be a doctor because he/she has fear of seeing blood.

- **LACK OF INTEREST.**

If a person has no interest on what he/she needs to do in future then it would be hard for a person to be able to know or to understand what he/she wants to do in his / her career in future

- **LACK OF SKILLS**

Sometimes a person might not be able to do the work that he/she wants to do due to lack of skill that one needs in order to do what he wants but lack of skills can make one not reach the goods to come to attain or do a career he likes due to lack of skills.

- **WEAKNESS**

Weakness can be not in order to make the person not reach his/her career some can be lack of motivation, fear to understand or even to get to know something this can also make a person not to be able understand the career / future he has.

1.3 WHAT TO DO INORDER TO REALIZE THIS FUTURE IS YOU NEED

- **HAVE INTEREST**

This is because you will know that it is something that you need and it will be your best thing because you will feel fine when you do it and it will make you know that by you being comfortable when you do it and realize that you are fine and no fear is in you when you do such a thing.

This is like when a doctor is interested in saving and treating people's life, he/she will study and master all the things he/she needs to know so as he/she can be able to treat a person in the future because that is what he/she loves and has interest in it hence will do anything to archive it.

- **REVIEWING YOUR GOALS.**

Young youth do not do not review their goals because they believe that money is something that can cure their struggles in life while somethings can not be cured by money, some think on what goal did they set in the past have they archived it and what else is left so as they can finalize their goals. This is because when you set goals and you have not reached it this means that you are not doing what you are interested in but you are just doing something because you gain money or for making people feel that you are fine and you have a job while in your heart you realize you have messed up everything you had plans with .

- **SET SHORT & LONGTERM GOALS.**

The goal are their to help him know if he or she has reached his / her target , if a person has long term and short term then it will make it easy for them to be able to archive their goals because if you don't have a plan then you wont be able to have a smooth success because you will want to try every thing and at the end lose every thing but having a plan will make you be able to know that you have archived your first step and now you have to walk your second step which will make your life a better place .

A short plan is the time when a person can plan so as he/ she can be able to make his/ her life work for sometime like for example a person wants to be a Doctor but because he has not yet found a job he or she goes to be a teacher of school subject at school and after sometimes he /she applies to a hospital and the person gets the job and the achievement of him having something to do all his life is a long plan form him . But the act of him being a teacher of science was a short plan so as he can earn income to help and support his need so there is an important to have a short and long term plan.

2. CHALLENGES FACED BY YOUTH TODAY

These are the hard and painful times that come into our life so as we can be able to test our abilities, the life challenges are the problems and difficulties that will come in your life and interfere with your quality time of your life and your goals.

2.1 CHALLENGES THEY FACE

- **MENTAL HEALTH PRESSURE**

When say mental health this is referred to the stress, anxiety and depression which a young person mostly pass through it a young person can be stressed on what to do which could make that person lose

concentration on what he/she will be planning to do so the mental health has to come to be stable to help a person be fully fine

- **FINANCIAL SUPPORT**

Money is a significance source to young people for many think about living cost, student fees and they think how to get money so as they can cover their living cost and student fee which makes them drop out of school so as they can be able to support their living cost and hence they lose their future in studies and life as well.

- **SOCIAL MEDIA PRESSURE AND ADDICTION**

This is a big negative impact for future as for now because many young youth use social media which could also lead to Mental health issues and this could be also harmful in the academic aspect and also the social development. The addiction of social media reduce spending time on personal activities which some of the personal activities also mean to create your future in your own way by even though at first then later you have to manifest it but due to social addict these are all not archived

2.2 WAY TO OVERCOME THE CHALLENGES.

- **POSTIVE ROLE MODELS.**

A Person should have interest from a good. Person that can inspire another person to want to reach where that person is at that particular time in either carer, lifestyle and even status in naturally.

- **DEVELOP GOOD HABITS**

A youth should have a habit of setting his/her timetable like creating routines and cues that trigger goal related actions to what that person want to archive in future.

- **STAYING POSTIVE**

The Person has to believe that he or she can be able to reach wear he or she want to reach by having motivation word like ‘I can learn” or “I can do it”, This help him/her have strength on himself.

3. SUM-UP

In the youth life while growing the youth should think on reaching his/her goals focus on building practical skills that would help him/her to be able to use them to reach his/her own goals. Youth should be taught about how should they plan their life and also they should be allowed to follow their own dreams so as they can be able to archive their own goals and need.

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ENHANCED PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE USING CUO NANOPARTICLES

Roguai Sabrina
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ABSTRACT

Urbanization has led to a significant increase in various forms of pollution, posing critical challenges for sustainable development and public health. Among these issues, wastewater treatment and the sanitation of potable water supplies have become central concerns, particularly due to the escalating levels of industrial pollutants in urban water bodies. Advanced oxidation processes (AOPs) have emerged as promising technologies for addressing water pollution in urban areas, offering effective solutions for the mineralization of toxic organic contaminants. A key method within this framework is heterogeneous photocatalysis, which leverages semiconductor materials like copper oxide (CuO) to degrade pollutants without introducing additional harmful chemicals.

Heterogeneous photocatalysis is particularly suited for urban applications due to its ability to break down organic pollutants into non-toxic byproducts through light-activated chemical reactions. The use of CuO as a photocatalyst in urban wastewater treatment offers significant benefits, as it minimizes the need for chemical additives and helps maintain water quality. In this study, CuO nanoparticles were synthesized using a simple co-precipitation method, optimized through controlled heating at 80°C, to enhance photocatalytic activity—an important factor for urban water treatment applications.

Characterization of the synthesized CuO nanopowder was performed using X-ray diffraction (XRD) and scanning electron microscopy (SEM), confirming the monoclinic phase of CuO with an average crystallite size of 30 nm. This nanoscale structure is essential for urban wastewater treatment as it increases the surface area available for reactions, thereby enhancing pollutant degradation efficiency.

SEM analysis revealed a three-dimensional, flower-like morphology in the CuO nanoparticles, a structure that optimizes light absorption and pollutant adsorption. These characteristics make CuO nanoparticles highly effective in degrading methylene blue (MB), a common urban water pollutant, demonstrating their potential in addressing wastewater challenges in urban environments. Given the growing concerns over water, soil, and air pollution in cities, the development and application of CuO nanoparticles in advanced water treatment technologies represent a significant investment opportunity for improving urban environmental sustainability. Moreover, the integration of such photocatalytic processes into urban water treatment systems can help mitigate the broader impacts of industrialization, construction, and social pressures on water resources in cities.

Keywords: CuO Nanoparticles, Photocatalytic Degradation, Urban Water Pollution, Wastewater Treatment Technologies

SIVAS INTERNATIONAL CONFERENCE ON SCIENTIFIC AND INNOVATION RESEARCH-V

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