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Research Article
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PROJECT MONITORING BASED ON VIEW OF ALL PROJECT PARTNERS AT DIGITAL PROJECT MANAGEMENT PLATFORMS

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Abstract: In the dynamic landscape of digital project management, effective project monitoring is critical for successful project outcomes. The emergence of digital project management platforms has revolutionized the way projects are monitored, enabling real-time collaboration and data-driven decision-making. Periodic site visits and gathering input from all project stakeholders are crucial for ensuring clear understanding of project progress by states institutional. With digital project management systems, on-site progress should be monitored in real-time and inclusive of all project stakeholders. The research investigates how collaborative monitoring fosters project progress of transparency and active engagement among project partners. By providing real-time visibility into project progress, tasks, and milestones, these platforms empower stakeholders with up-to-date information, enabling agile decision-making and prompt risk mitigation. This study explores how digital project management platforms integrate site monitoring evaluations and reporting tools, providing valuable data-driven insights into project performance. By considering periodic analytics, project partners can improve resource allocation, decision making process against possible bottlenecks at construction stages and boost productivity and inform states institutional to monitor project progress closely. Furthermore, the research examines the influence of these platforms on communication dynamics, promoting communication and efficient information exchange among project partners. Such enhanced communication capabilities result in improved team cohesion and collaboration, driving the project forward with synchronized efforts. In this study, the focus lies on tracking the progress of contractual agreements through digital platforms, enabling all stakeholders to monitor advancements. Specifically, the investigation centers on how the designated contractor responsible for project execution and the consulting firm appointed by the project owner can effectively track project progress on a periodic basis using digital platforms. In the context of transportation projects in Türkiye, a digital project tracking system has been developed for the Ministry of Transport and Infrastructure, through which data obtained from on-site visits and consultant opinions regarding project advancements are shared with the Ministry. Subsequently, the responsible contracting authority, guided by the consultant's feedback, can respond and evaluate progress accordingly. This approach ensures that project advancements are accurately monitored by all stakeholders of the project. To do so, this study investigates the utilization of the prepared digital platform to facilitate rapid and precise contract monitoring by all project stakeholders, encompassing the opening information and assessment evaluations based on stakeholders' perspectives.

Keywords: Project management, Project monitoring, Digital project management

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1. Introduction

The project management process is a structured and systematic approach to planning, executing, and closing projects, made possible by the coordinated efforts of diverse project partners. The process commences with project initiation, where objectives, scope, and stakeholders are defined. Traditional project management process composes of simply consultants, owners, and contractors. Effective collaboration and communication of them are essential in the project process. Consultants play a crucial role at the project initiation stage, conducting feasibility studies, defining project scopes, and providing expert guidance on the project's strategic direction. Consultants' technical guidance and insights contribute to the project's success and quality. Owners, as project sponsors, provide the vision and resources required to drive the project forward. Their involvement throughout the project lifecycle, from inception to closure, ensures that the project aligns with strategic goals and meets expectations. If public projects' construction process is taken into account, the owner, as an institution, serves as the driving force and ultimate decision-maker in the project management process. Their clear vision, effective resource allocation, and active engagement are vital in ensuring the project's success and aligning it with the institution's strategic objectives. Once the project is greenlit, constructors step in, taking charge of construction activities. They work closely with architects and engineers to ensure the design is translated into

reality while adhering to quality and safety standards. Throughout this dynamic process, effective communication and collaboration among all partners are vital to address challenges, make informed decisions, and meet project milestones. Ultimately, successful project management hinges on the collective efforts of these partners, harmoniously working together to bring projects to fruition on time, within budget, and to the highest standards of excellence.

While these project management processes suit projects with clear requirements and predictable outcomes, they may lack the flexibility to address complex and rapidly changing endeavors. Close contact with project partners is essential during the project duration, especially in the face of unexpected conditions or challenges. Maintaining open and effective communication with all stakeholders, including consultants, contractors, suppliers, and the project owner, allows for prompt identification and response to unforeseen issues. When unexpected conditions arise, such as changes in project scope, unforeseen risks, or resource constraints, close contact ensures that relevant parties are informed promptly. This enables collaborative problem-solving, where partners can collectively assess the situation, brainstorm solutions, and make informed decisions to adapt to the changing circumstances. Regular updates and close coordination foster a sense of teamwork, enhancing the project partners' ability to work cohesively and proactively address any obstacles that may arise. By staying in close contact, project partners can swiftly adjust project plans, reallocate resources, and modify strategies to keep the project on track and achieve successful outcomes despite unexpected challenges. Consequently, more adaptive and iterative methodologies have emerged, prioritizing collaboration, adaptability, and customer feedback to better handle dynamic and uncertain project environments.

In today's rapidly evolving technological landscape, the digital project management process has emerged as a paramount strategy to ensure the successful execution of complex endeavors. Integrating cutting-edge digital tools and methodologies, this dynamic process fosters streamlined workflows, enhanced communication, and unparalleled project visibility. At its core, the digital project management process revolves around a series of carefully orchestrated stages, each playing a pivotal role in achieving project objectives. Furthermore, recognizing the significance of collaborative partnerships, this process involves diverse stakeholders working harmoniously to navigate challenges and capitalize on opportunities.

1.1. Studies Related to Digital Project Management

Partnering is considered a vital project management strategy for enhancing project performance by fostering better working relationships (Bennett and Jayes, 1995; Egan, 1998; Bayliss, 2002). In the past ten years, the practice of partnering in construction has significantly enhanced the working relationships between clients and contractors. This approach aims to shift the traditionally adversarial construction culture to one grounded in trust and transparency. To achieve these goals, various partnering tools have been developed, such as workshops, review meetings, team-building exercises, incentives, and social functions. The primary purpose of these tools is to align the objectives of the contracting parties towards a common goal, fostering a more cooperative and effective project team (Bennett and Jayes, 1995). A few research have shown the most important requirements for a successful partnership. These requirements include dedication, confidence, sincerity, common objectives, collaborative tools and processes, participation of appropriate stakeholders, leadership, and continual assessment (Black et al., 2000; Ng et al, 2002). Others look at partnership applications, particularly the use of partnering to eliminate disagreements and foster a more cooperative working atmosphere (Bresnen and Marshall, 2010; Li and Cheng, 2000). There is also a wealth of literature that examines the critical factors of successful partnering (Bennett and Jayes, 1995).

The idea of partnership is now widely seen as a great way to build relationships between organizations in public sector management (Friend, 2006). This arises from the traditional belief that government agencies should collaborate with other governmental bodies, non-profit organizations, or businesses to improve service and goods delivery while optimizing resource utilization. Although the value of collaborative approaches is widely acknowledged, partnerships have a potential to be fail in practice (Jacobson and Choi,2008). Therefore, complexity and ambiguity in defining and measuring project success have been acknowledged as a problem since awareness of success criteria has developed (Jugdev and Muller,2006). Although project management success and deliverable success are not entirely dependent on each other, unsuccessful project management can undermine the success of the deliverables. Therefore, the project and its resulting products cannot be viewed in isolation (Varajao et al, 2021).

With the development of information technologies, the use of software tools in the evaluation project success has increased (Petter and Vaishnavi, 2008). These advancements have made project monitoring more precise and efficient, allowing for real-time tracking and analysis of various project metrics. The success of a project is now more quantifiable, as stakeholders can easily monitor activities, milestones, and progress through sophisticated software solutions. This enhanced visibility ensures that any potential issues are identified and addressed promptly, leading to more informed decision-making and better resource allocation. Consequently, project stakeholders can collaborate more effectively, ensuring that the project's goals are met and that the deliverables are of the highest quality. The integration of information technology in project management has thus become indispensable for achieving and maintaining project success.

In project management, working together with partners is essential for success, but there can be difficulties that slow down the project's progress. With the help of information technologies, technological tools allow project partners to fully understand the detailed complexities of the project's timeline (Fernandes et al, 2021). By using platforms like project management software, communication tools, and task trackers, partners can see project schedules, task assignments, resource distribution, and overall progress in real-time (Marnewick and Marnewick, 2022).

The advancement of Artificial Intelligence (AI) has created new opportunities for the construction industry. It has the potential to increase annual productivity growth from 0.8% to 1.4%, and by 2030, the global construction market is expected to expand by 85%, reaching a value of USD 15.5 trillion (Regona et al, 2022). AI technologies such as automation, machine learning, and predictive analytics can significantly revolutionize the construction sector by enhancing project efficiency, reducing waste, and optimizing resource management. AI technologies, including automation, machine learning, and predictive analytics, have the potential to completely transform the construction industry by increasing project efficiency, cutting waste, and improving resource allocation (Darko et al, 2020).

This transparency helps prevent delays by enabling quick decision-making, identifying challenges early, and efficiently allocating resources (Tam et al,2020). AI also facilitates access to online training materials, enhancing skills and accelerating project completion (Pan and Zhang, 2021). Building Information Modeling (BIM), a 3D model-based approach, provides valuable insights for planning, designing, constructing, and managing infrastructure in engineering, construction, and architecture (Regona et al, 2022). The industry is exploring machine learning techniques to identify and resolve conflicts among various design models during the planning phase, thereby minimizing rework (Blanco et al, 2018). Additionally, machine learning generates optimized 3D models of plumbing, electrical, and mechanical systems to ensure they integrate seamlessly with the structural design. Nevertheless, the construction industry lacks adequate cybersecurity awareness, which makes it highly vulnerable to cyberattacks that can result in project delays, financial setbacks, and other serious negative impacts (Parks,2021). Although cybersecurity standards specific to the construction industry have not been established, many countries are addressing these challenges by adopting existing frameworks such as the National Institute of Standards and Technology (NIST), General Data Protection Regulation (GDPR), ISO/IEC 27000, and Center for Internet Security (CIS) Controls. These frameworks provide structured approaches for managing cybersecurity risks and mitigating potential threats (Yao and Sato, 2024). Throughout the project, clients or end-users stay involved, giving feedback and approving deliverables. This client-centered approach, supported by digital tools, ensures the project meets expectations and reduces misunderstandings. Additionally, stakeholders from regulatory bodies or other organizations may join to ensure compliance with industry standards, emphasizing the need for a clear and accessible view of the project's timeline and details (Sallinen et al,2011). In this complex network of partnerships, each participant's role is crucial, working together to ensure the project's success. Digital tools used in modern project management enhance this collaborative environment, minimizing bottlenecks that could delay the project and keeping it streamlined and responsive to the demands of today's projects.

2. Materials and Methods

In Türkiye, there are 14 institutions under the Ministry of Transportation and Infrastructure. Under the auspices of the Ministry of Transportation and Infrastructure, there are approximately 3000 contracts in progress, overseen by these institutions that provide services in all sectors such as highways and railways. The activities carried out by the institutions affiliated with the ministry are regularly monitored and informed by the central units of the ministry throughout the process. The Ministry of Transport and Infrastructure has been followed the projects of its responsibility as shown in Figure 1.

All developments in the project are reported by the consultant and the contractor to the responsible Minister’s members to control and approve the developments in field. These developments are detail-reported to the region and Minister Head Departments to follow the field's cost and physical performance progress. In traditional project management methods, all these information transfer about project progress is done not only via mail or in word/excel type of documents. It has become necessary in the digitalized world to monitor many planned, ongoing and completed infrastructure projects, especially with today's technologies. To implement new technologies in infrastructure projects and increase the project management knowledge within the changes in the digital world, digital project management system (DPMS) has been implemented by the Minister of Transportation and Infrastructure in Türkiye since 2020. Within this system, the Ministry is able to have close knowledge about ongoing projects and can monitor significant projects for the country's future through one system, involving all stakeholders.

DPMS provides an efficient and user-friendly platform by digitizing the data of ongoing transportation projects. DPMS not only provides an excellent monitoring environment for conditions, costs and general activities which apply to the transportation projects, it also allows users to view geographical based information such as locations and the routes of the linear transportation webs. This comprehensive system also lets users see upcoming and past ceremonies for completed transportation lines.

2.1. Ecosystem of DPMS

DPMS is a system in which all project stakeholders are

involved, so contractors and consultancy firms have been a part of the system. System data entry is expected from consultancy firms. If there is no consultancy firm on project, Minister's members are duty to give data to system. They must periodically enter data related to performance (physical and cost progress) planning, reports, and photos.

The Institutions of Ministry do sustainability of the system. The data entrance process of the system depends on the hierarchy of the institution and if the institution coordinator approves the entered data, system will launch the information. This helps control the data and allows it to be corrected in case of a possible error, before it is reported to the Ministry. When each data entry process is completed, information is provided from the system as mail or pop-ups for the approval and control of the relevant units. This data-driven system can be easily connected from anywhere with internet access. Figure 2. represents the data-driven DPMS working principles between all stakeholders.

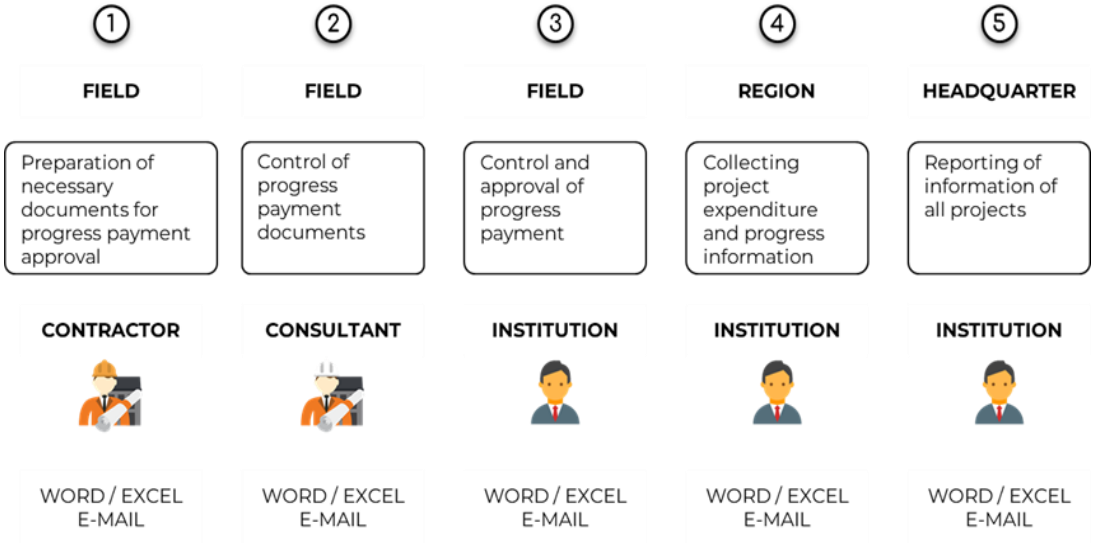

Figure 1. Change of organizational relations - project reporting process-traditional methodology.

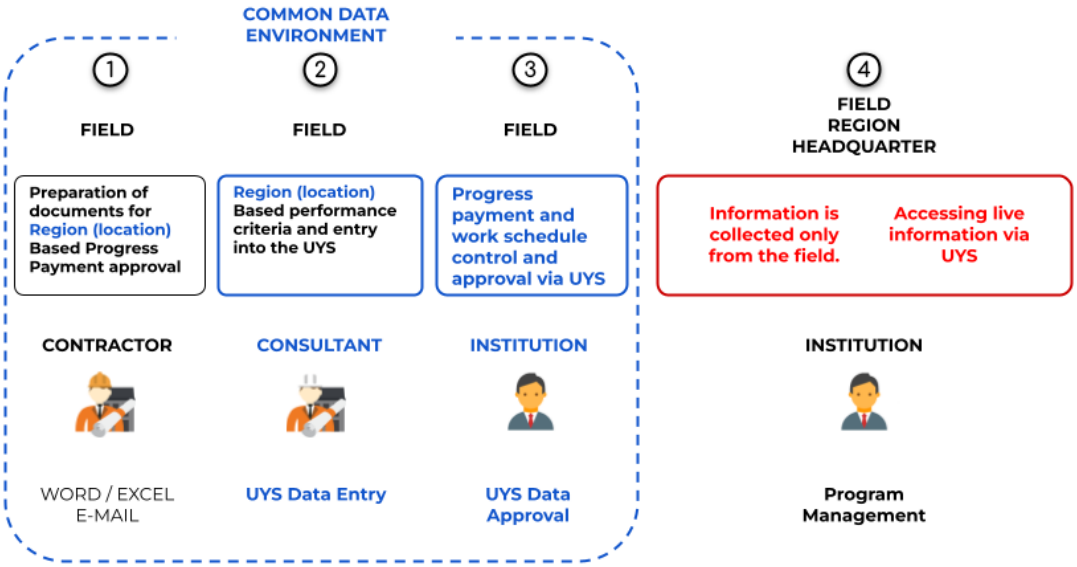

Figure 2. Change of organizational relations of project monitoring process with DPMS methodology.

2.2. Workflow of Project Monitoring at DPMS

All project stakeholders periodically monitor the progress status of the project through the DPMS using the Opening Evaluation module. The tasks assigned by the Ministry for tracking target and vision projects are linked with other modules in the project management system, containing geographical information and contract details, for the works visited during field visits by the consulting firm. This way helps to see contract routes and construction progress statuses and ensure the monitoring of critical activity follow-ups. The project evaluation process is conducted through the DPMS platform in a transparent and understandable manner for all stakeholders. As shown in Figure 3., the administration first requests input from the consultant and then, based on the consultant's feedback, seeks a

response from the contractor. All parties are given a 15-day period to provide their responses. During this time, evaluations can be documented in the system with accompanying reports and relevant visuals. The request can remain open at the discretion of the administration, or they may require periodic responses at specified intervals.

Evaluation processes begin with creating the "Evaluation Card" and linking the related contract that took part in the DPMS database. After completing this step in the system, an immediate notification will be sent to the issued contacts to inform that an evaluation process has been begun. After completing the further tasks aforementioned, all data and documents will be uploaded to the system. After confirming the uploaded data, completed and checked out, another notification will be sent as previously done.

The Ministry of Transportation and Infrastructure has the leading role for the main purpose of the evaluation module. Always in charge of both the evaluations of consultants and the institutions which operate the projects on site. On behalf of the consultants on duty, the ministry becomes more capable of taking control over these comprehensive projects. Sharing the duty of project management with the consultants, the ministry utilizes the projects more effectively, hand on and objectively which will be served to the public for many years. So the evaluation module gathers opinions of each party in its body for more purposeful data collection. Briefly it gets easier to direct the projects run by institutions under the roof of the ministry.

The ministry serves as the central control unit for projects because ministry is required to manage the process not only on-site but also remotely due to the instructions and responsibilities it provides. Therefore, it should be emphasized that the consultant is responsible for fulfilling field visit and inspection tasks and providing an impartial evaluation of the process based on the instructions and responsibilities given. Since the process is also monitored by the Ministry through the relevant/responsible institution, input from the responsible unit's perspectives and evaluations is necessary, not just relying on the consultant's opinion. The system brings all these partner of the projects together. The observations made by the consulting firm during field visits, the findings generated based on the data collected, and the recommendations for the progress of the work are entered into the system. In line with this, the prepared reports and field visuals are also included in the system. Hence, after conveying and obtaining approval of the consultant's opinions to the Ministry, they are sent to the institution after the consultant approval process to provide information on the consultant's opinions and the status of relevant contracts. Each evaluation will be visible to the institution and with respect to that application, opinions of each party will be reviewed objectively by the ministry. Also this system allows institutions to be more aware of the improvement of the contracts issued to themselves due to received notifications by other parties. Above all, project management becomes more open, accessible and objective. Notifications are sent to users defined in the system regarding the uploading and approval processes of projects within the system. These notifications can be sent both via e-mail and SMS. The processes with stakeholders and notifications made through the system are carried out as shown in the workflow in Figure 3.

2.2. Data Entering Process of Opening Evaluation Module at DPMS

DPMS incorporates a good deal of categories and modules of categories which connects the collected information between its database. Opening Evaluation, one of the principal services provided by the system, is a module that is designed for tracking the facility openings of the most essential transportation lines marked by the ministry based on the targeted service year.

By using preset geometries of the projects which are linked to their subcontracts, the "Project Openings Module" provides necessary information under a specific layer of the main interface.

The system frequently employs various colors, shapes, and legends on the main interface map, which change according to the selected layers. Data for this specific submodule is gathered through onsite visits and engineering evaluations based on common planning and cost control disciplines. The Ministry has a dominant leading role in the projects it operates, but many other participants are involved, such as sector-specific agencies, contractors, and subcontractors. Creating objective and well-provided information requires the involvement of all parties. The Investment Planning Monitoring and Program Management project has been providing consultancy services to the ministry since 2020, making the transportation management system available to the institutions in charge. This consultancy organization, operated by the ministry, acts as a catalyst between the ministry and its associated agencies at a whole new level. As a result, this consultancy project becomes the right hand of the ministry, offering on-site and digital project management for all parties. In the Project Openings module, linked to its main module named "Request Tracking Module," consultants start the engineering evaluation for the projects by first visiting the site and documenting the results and visuals from the construction site. Using this submodule's database, consultants request a report with similar criteria from the related party. Projects are reviewed based on the current phase of the project in terms of costs, physical improvement, and assets, the planned date of the facility opening and its comparison with the targeted date determined by the ministry, and evaluating whether the project is reaching the target year. Finally, selecting the appropriate label for this evaluation in the system, such as "Opening is available," "Opening is not available," and "Partial or Conditional Opening is Available," is necessary for the map view.

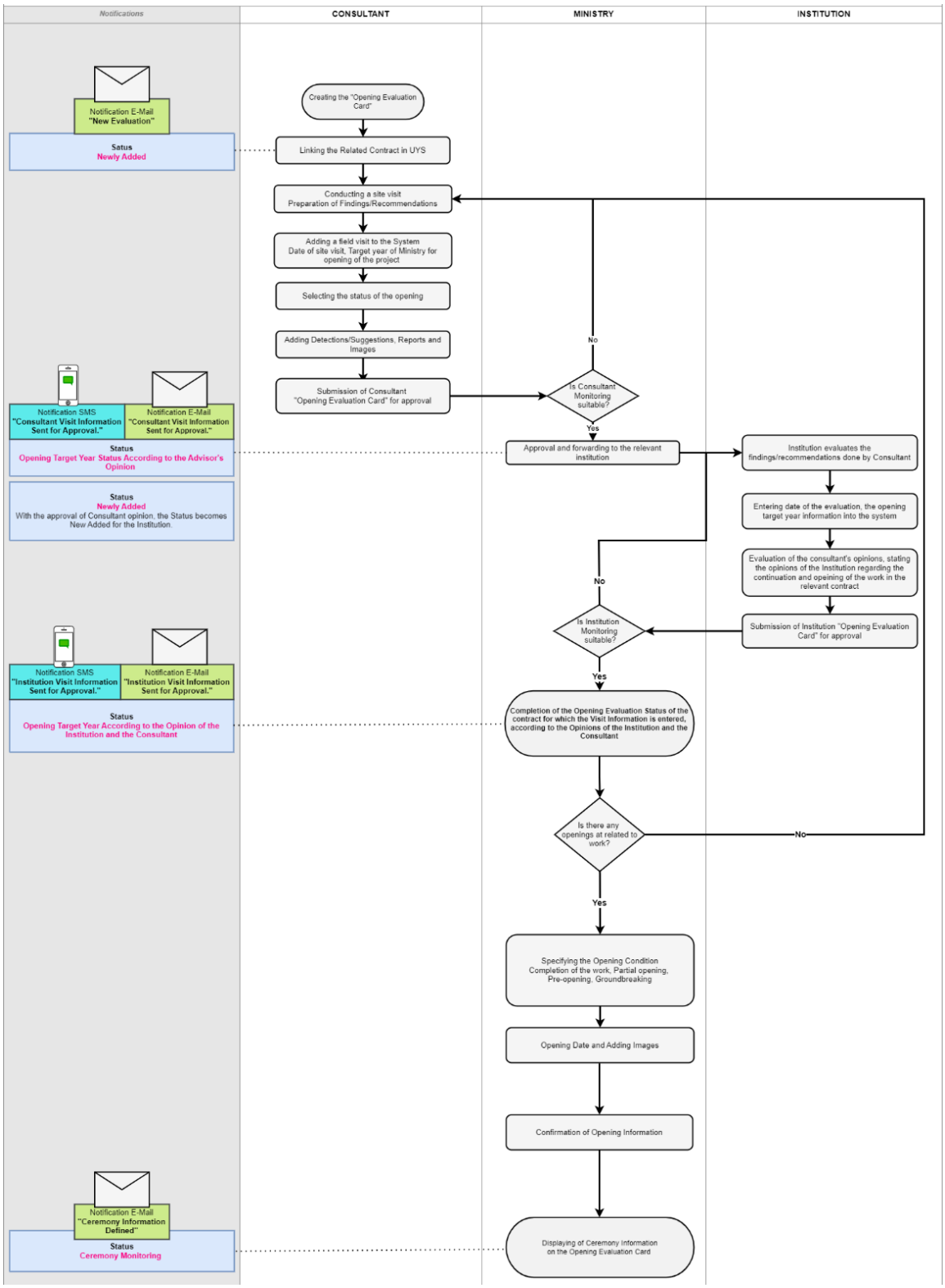

Figure 3. Project openings workflow.

This module is mainly created for examining ongoing projects, but some contracts are detected as completed, or the information obtained by the parties in charge may differ from what is previously known. Such data must also be transferred into the system. In this case, DPMS provides the necessary section under this submodule as a whole new layer tagging the projects under the title of "Ceremonies." These ceremonies typically include laying the foundation ceremony, final face ceremony (often used for tunneling), partial or sectional opening ceremony, and individual opening ceremony. A similar color code is used to define the openings and reviews from executors, but a non-circular shape with a black frame is preferred for identifying openings. Different scenarios are shown with respect to all stakeholders in the Figure 4. The inner circle reflects the consultant's

reviews, while the outer circle shows the institution's opinion. Both openings that have occurred in the project timeline and recent evaluations that have been confirmed will be visible. When a project is completely finished, the latest unpublished review will be labeled as “Opening is Available” due to its finalized state “Individual Opening” right after the ceremony. This setting for the latest review will also be green.

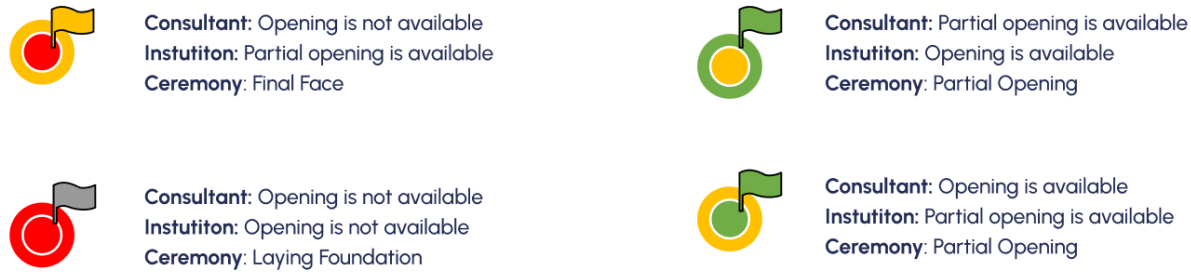

Figure 4. Icon combinations on the map view of the evaluation module when an evaluation and a ceremony are added to the linked contract.

3. Results and Discussion

Projects which have been evaluated and ceremony information added will be shown into the “Evaluation card” of the associated contract. DPMS is mainly based on the contracts which summarize projects under the ongoing disciplines. So tying up the related issue with the corresponding contract is crucial.

This point of view is achieved by the examination of ongoing projects as well as the projects executed in the past and it's named as “Project Tree'' by the consultant and the ministry.

Although many infrastructure projects can be defined by few disciplines such as highway projects, some of the larger scaled projects become more and more complicated during the execution. Having numerous new applications that require brand new contracts became the most unwanted problem of project management for the ministry in recent years. The Department of Strategy and Budget follows an alphanumeric identification system containing information of year of the funded project and numbers sorted by previous applications to keep all expenses and funds in track. Congregating similar contracts under similar issues keeps even the smallest data in track since the amount of the expenses might get too many to follow. But this type of application is not compatible with the Transportation Management System. So DPMS has its own way of collecting data of the contracts which is a project tree containing the related subcontracts by their unique ID numbers given. An Evaluation Card which is linked to a specific contract contains two sections. First, a timeline view demonstrating the evaluations and ceremonies second, segments including detailed information such as texts, attached documents and visuals.

Evaluation processes begin with creating the “Evaluation Card” and linking the related contract that took part in the DPMS database. After completing this step in the system, an immediate notification will be sent to the issued contacts to inform that an evaluation process has been begun. After completing the further tasks aforementioned, all data and documents will be uploaded to the system. After confirming the uploaded data, completed and checked out another notification will be sent as previously done.

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3.1. Potential Drawbacks and Bottlenecks

Despite the clear benefits, several potential problems and challenges could hinder the effective use of digital project management systems. Relying on real-time data entry means all team members need to consistently provide accurate information. Mistakes or delays in data entry can lead to wrong decisions and project delays. Setting up a digital platform requires a lot of technical infrastructure and expertise. Technical issues, like software bugs, network problems, or difficulties in integrating with existing systems, can disrupt project monitoring and management. It's crucial to ensure that all users are well-trained and comfortable with the digital platform. Resistance to change or lack of technical skills among users can slow down adoption and reduce the system's effectiveness. Managing sensitive project data digitally raises concerns about data security and privacy. Robust cybersecurity measures and compliance with data protection regulations are vital to prevent data breaches and unauthorized access. Integrating the digital project management platform with other tools and systems used by different stakeholders can be

challenging. Lack of compatibility can lead to isolated data and hinder smooth communication and collaboration. Using digital platforms effectively requires a significant initial investment in technology and ongoing maintenance costs. Budget constraints and resource allocation issues may pose challenges, especially for smaller organizations. Lastly, while digital platforms can enhance communication, ensuring active and consistent engagement from all stakeholders can be difficult. Variations in commitment levels and responsiveness can impact the overall effectiveness of the project management process.

4. Conclusion

This study highlights the significant role that digital project management platforms play in enhancing project monitoring and collaboration among all stakeholders. By integrating real-time data, these platforms provide up-to-date visibility into project progress, facilitating agile decision-making and prompt risk mitigation. The research demonstrates how collaborative monitoring, supported by digital tools, fosters transparency and active engagement, which are critical for the successful execution of complex projects.

The implementation of the Digital Project Management System (DPMS) by the Ministry of Transportation and Infrastructure in Türkiye serves as a robust example of how digital solutions can transform traditional project management approaches. The system's ability to incorporate real-time data entry, evaluation processes, and geographical information significantly improves project tracking and evaluation. By bringing together contractors, consultants, and ministry officials into a cohesive digital ecosystem, the DPMS enhances communication, ensures accurate monitoring, and promotes effective decision-making. Moreover, the study underscores the importance of periodic site visits and the incorporation of feedback from all project partners in achieving accurate and comprehensive project evaluations. The findings suggest that the integration of digital tools not only streamlines project management processes but also aligns with the strategic objectives of public institutions, ensuring that projects are completed on time, within budget, and to the highest standards. Overall, the adoption of digital project management platforms represents a paradigm shift in project management practices, offering a more efficient, transparent, and collaborative approach to managing large-scale infrastructure projects. Future research should focus on exploring the long-term impacts of these digital tools on project outcomes and the potential for further innovation in this field.

Author Contributions

The percentage of the authors' contributions are below. All authors reviewed and approved the final version of the manuscript.

	H.İ.	E.C.S.
C	60	40
D	60	40
S	60	40
DCP	60	40
DAI	60	40
L	60	40
W	60	40
CR	60	40
SR	60	40

C=Concept, D= design, S= supervision, DCP= data collection, and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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EXAMINATION OF THE PEACEFUL USES OF NUCLEAR ENERGY IN TURKISH LEGISLATION

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Abstract: Population growth, industrialization and technological advances increase the demand for energy. Due to problems such as global warming, environmental pollution and destruction, the trend towards alternative energy sources continues on a global scale. For this reason, the use of nuclear energy, one of the secondary energy sources, has tended to increase in recent years. Reasons such as the geographically uneven geographical distribution of resources that are raw materials for energy among countries and their exhaustibility, fluctuations in energy prices and the economical production of nuclear energy are among the reasons why countries in the world turn to nuclear energy. A number of accidents at nuclear power plants have had a negative impact on the perception of nuclear power plants, but for different reasons, nuclear energy is gaining popularity again. Nuclear power plants are the first thing that comes to mind when it comes to nuclear power, but it is also used effectively in medical treatments and applications of various branches of science as well as energy production. In global energy production; the fact that it aims to reduce carbon emissions by providing more energy production within the scope of sustainability, the continuous and uninterrupted continuation of electricity production using nuclear, the production of electricity at more affordable costs in nuclear power plants compared to other power plants (thermal, renewable, etc.), the fact that greenhouse gas emissions are almost negligible, and the use of nuclear technology in many fields such as physics, medicine, transportation, agriculture as well as energy production have made nuclear energy back on the agenda of countries in recent years. In nuclear energy, nuclear waste and their storage processes continue to be discussed as a problem in this process. For these reasons, the possibility of peaceful use of nuclear power has been questioned in academic platforms and various criteria have been determined. This article examines Türkiye's compliance with the criteria for the peaceful use of nuclear energy and clarifies the development process in this regard. Türkiye's legislation on nuclear energy, international conventions, nuclear safety, radiation control criteria and compliance with national legislation will be examined.

Keywords: Nuclear, Energy, Peaceful use, Legislation

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1. Introduction

Global final energy consumption is expected to increase by around 30 percent by 2050 and electricity generation is expected to double (Yıldırım, 2019). The share of coal in electricity generation remains the dominant energy source worldwide, currently around 36% (Gizlenci et al., 2012). The share of nuclear, renewables and natural gas has increased over the last 40 years (IAEA, 2015). Today, nuclear energy contributes about 10% of global electricity generation (IAEA, 2015).

Electricity generation from fossil fuels negatively affects CO2 gas emissions, which have a significant share in global warming (Demirgil and Birol, 2018). For this reason, nuclear energy is on the world agenda because of its low cost and environmentally acceptable energy needs (Çanka, 2011).

The economic crisis that accompanied the pandemic, the decrease in natural gas and oil resources and the increase in fossil fuel prices have been effective in reshaping energy markets and reviving interest in nuclear energy.

The first countries to produce energy from nuclear energy sources were the United States and the former Soviet Union in late 1955 (Tüylüoğlu and Türkan, 2023). After the devastating effects of two nuclear weapons containing uranium and plutonium, which were used for the first time, the need for an international, impartial institution started to be felt due to nuclear technological discoveries (Muray and Holbert, 2020) and the fears and concerns caused by the use of these technologies (Koltukçu, 2010).

Despite the use of the first nuclear bomb, the then US President Dwight D. Eisenhower made a speech titled "Atoms for Peace" at the United Nations (UN) General Assembly on December 8, 1953, which marked the first step in the establishment of the Agency that would determine the content and details of the use of the atom for peaceful purposes. Following Eisenhower's initiative, the charter of the International Atomic Energy Agency (IAEA) was unanimously approved by 81 countries on October 23, 1956 and entered into force on July 29, 1957, and started its activities as an autonomous organization within the UN (Kavaz, 2021).

In the second article of the Agency's statute, the Agency's two main missions are stated: "The Agency shall aim to accelerate and expand the contribution of nuclear energy to peace, health and prosperity throughout the world." It is also emphasized that efforts will be made to ensure that any nuclear activities controlled or supported by the Agency do not serve military purposes (Kara and Türkan, 2022). The Organization is headquartered in Vienna and has offices in Toronto, Tokyo, New York and Geneva.

The Agency's board of 34 members, which changes every two years, convenes quarterly to discuss the work of the organization and issues related to global nuclear security (Kara and Türkan, 2022).Türkiye has been a member of the board of directors since September 2022.

A general assembly meeting is held once a year with the participation of all members, and member countries provide information about their work in the nuclear field and the projects they carry out in cooperation with the Agency (Kocaoğlu, 2010).

The IAEA has signed two binding agreements with its member states for nuclear safety and security: the Comprehensive Safeguards Inspection and the Additional Protocol. These agreements allow the Agency to inspect the nuclear activities of member states, in which case the Agency can determine whether nuclear material is being used for peaceful purposes (Özdemir, 2020).

Pursuant to the aforementioned agreements, countries are obliged to regulate their legislation in a way to include the topics of nuclear and radiation safety, radiation protection, nuclear liability and nuclear security.

Today, 440 nuclear reactors are in operation and 54 nuclear reactors are under construction in the world. The electricity generated in nuclear power plants corresponds to approximately 10% of the world's electricity supply (Ministry of Energy and Natural Resources, 2023).

The country with the most nuclear power plants in the world is the United States of America with 100 plants. The country that uses nuclear energy the most in electricity generation is France with 75%. Ukraine meets 51% of its energy needs from nuclear energy, Sweden about 30%, Belgium about 40%, the European Union 26%, South Korea about 30% and the USA 20%. The countries with the least nuclear energy capacity are Armenia, Belarus, Iran, the Netherlands and Slovenia with 1 nuclear reactor each (Miden and Verplanken, 1990).

Historically, nuclear reactor accidents corresponding to level 6 (serious accident) and level 7 (major accident) have occurred. One of the most important of these accidents was the thermal explosion at the Mayak Nuclear Plant in Russia in 1957, which was the first. The 1986 Chernobyl accident is also one of the largest nuclear technology accidents in history (Özdemir, 2020). Another major nuclear power plant accident in history occurred in 2011 at the Fukushima Daiichi Nuclear Power Plant due to the tsunami that occurred after the Japanese earthquake (Katsuya, 2001).

Along with the energy production from nuclear power plants, there are ongoing debates about its environmental impacts (Akleyev et al., 2017). There are various ideas about the positive and negative aspects of nuclear energy. While reasons such as nuclear energy being an alternative to fossil energy sources, being economical and nuclear energy being a beneficial technology for humanity are the positive aspects of nuclear energy, reasons such as nuclear accidents in the past and the high initial investment cost are considered as the negative aspects of nuclear energy. Therefore, it is important to examine the positive and negative aspects of nuclear power plants in economic and environmental terms.

The high potential reserves of nuclear power, the fact that they do not cause greenhouse gas emissions that cause climate change, the recycling of nuclear waste, the separation of fossil materials (uranium, plutonium) from fission products remaining in the burnt fuel with reprocessing in advanced technologies and their reuse in fuel production (Çetinkaya, 2019) and the fact that they do not adversely affect air quality are included in the literature as positive aspects.

On the negative side, radioactivit poses a danger due to pre-production, production phase and post-production wastes (Muray and Holbert, 2020), and although studies have shown that the risk of accidents in nuclear power plants is low, the destruction it will cause in huge areas in the event of an accident negatively affects people and nature (Uyar, 2017).

Despite all these negativities, it is important to obtain electricity from Nuclear Power Plants and to produce energy in this way today when energy costs are high. Studies in many fields such as the fight against cancer, the development of X-ray devices, the protection of water resources with isotopic technique, the application of drip system in regions with water shortage using nuclear technology, the measurement of pollution in the seas and the determination of its causes are carried out with nuclear energy. In order to catch up with this technology in the world and considering the high amounts paid for energy imports in our country, nuclear energy is recommended as a necessary alternative.

The peaceful use of nuclear energy, taking into account its positive and negative aspects, aims to eliminate the danger dimension.

1.2. Nuclear Energy in Türkiye

The need for energy is constantly increasing in Türkiye (Kavaz, 2021). Evaluating Türkiye's energy policies and investments in energy production, it is stated that the steps towards alternative energy sources are insufficient and the efficient production, consumption and capacity of energy are weak (Erkök, 2022). This situation brings with it concerns that the country may face an energy crisis (Eş and Mercan, 2016). As a result, it is seen that nuclear energy is an important issue in terms of its economic growth, symptoms, technological

developments and energy policies (Furuncu, 2016).

Efforts to obtain nuclear energy in Türkiye started in 1956 and the Atomic Energy Commission was established under the Prime Ministry in the same year. Subsequently, in 1961, the Nuclear Research and Training Center research reactor was put into operation in Büyükçekmece (Gizlenci et al., 2012).

The establishment of the first nuclear power plant in Türkiye was planned in 1967, and the necessary studies for this purpose were commissioned to a Swiss consortium, but the plant, which was planned to be completed in 1977, could not be established due to the economic and political conditions of 1970-71 (Pamir, 2003).

The Department of Nuclear Power Plants was established within TEK, work to build the plant resumed in 1970, site selection for the plant was completed in 1976, and a license was obtained for Akkuyu. However, due to the failure to make payments and the coup d'état, the result could not be reached.

The Atomic Energy Commission and the Atomic Energy Authority were reorganized in 1982 with Law No. 2690. The purpose of the Authority is to generate electricity from nuclear energy, to encourage and regulate studies, to license and inspect nuclear facilities.

In 1983, with the Decree Law No. 166, the Nuclear Power Plants Corporation was established to meet a portion of the country's electrical energy needs; however, the Law No. 3743 enacted in 1991 was annulled because the conditions of the establishment decree were not fulfilled.

During the reorganization of TEK, the Nuclear Power Plants Department was closed in 1988.

In 1995, work accelerated again, and the Nuclear Project Group was given the status of a directorate and then a presidency.

In 1997, an international tender for nuclear power plants was launched and bids were received in October 1997 (Temurçin and Aliağaoğlu, 2003). NPI (France-Germany), AECL (Canada-Japan), WESTINGHOUSE (USA-Japan) consortiums participated in the tender (Kaya, 2012). In 2000, the government announced that it was abandoning the finalization of the project and the establishment of a nuclear power plant in Türkiye.

In 2004, the then Minister of Energy and Natural Resources brought the issue of nuclear power plants back to the agenda. He announced that technical examinations on nuclear power plants were underway, that the specifications for their establishment had reached the specification stage and that negotiations would be held in the near future. He stated that the operation of the plants would be in the private sector and that research on the location of the plants was ongoing, and that the Akkuyu region in Mersin, which had previously been identified as the site for the plant but was opposed by environmental groups, was on the agenda as one of the alternatives.

Subsequently, 7 million TL was allocated to the investment budget of the Electricity Generation Co. and the Turkish Atomic Energy Authority for the power plants, which were included in the 2005 investment program.

In January 2007, the "Nuclear Energy Law" was enacted, aiming to build three 5,000 megawatt nuclear power plants between 2010 and 2020.

In May 2010, the Russian Federation and the Republic of Türkiye signed a Cooperation Agreement for the construction of the Akkuyu Nuclear Power Plant. On December 13, 2010, in accordance with the terms of the agreement, the Russian side established the Akkuyu Nuclear Joint Stock Company project company in the Republic of Türkiye (Ağır et al., 2020).

In 2013, after a visit to Türkiye by Japan, an international agreement was signed to build a nuclear power plant. The other nuclear power plant project in Türkiye is the Sinop Nuclear Power Plant. On June 27, 2019, Turkish President Erdoğan announced in an interview that the Sinop project was halted due to rising costs.

In October 2015, the Minister of Energy and Natural Resources announced plans to build the third nuclear power plant in İğneada.

In March 2022, the Nuclear Regulation Law entered into force.

1.3. Turkish Nuclear Energy Legislation

1.3.1. Constitution of 1982

The legal framework regulating nuclear energy is structured in accordance with the normative hierarchy of the Turkish national legal system. The 1982 Constitution does not contain provisions directly addressing nuclear energy or nuclear activities. Instead, the importance of nuclear energy is recognized indirectly through various constitutional provisions. These include the right to life under Article 17, the right to live in a healthy and balanced environment under Article 56/1, and the state's obligation to protect the environment and natural heritage under Article 56/2. . While these constitutional provisions do not explicitly prohibit nuclear activities in Türkiye, they impose strict obligations on the State. They require the State to exercise the utmost care at every stage of nuclear activities.

Furthermore, the Constitution contains specific provisions that indirectly affect the siting and development of nuclear energy facilities. Article 169, which focuses on the protection of forests, and Article 43, which addresses the protection of coastlines, are particularly relevant in this context. These articles impose certain limitations on the establishment of nuclear power facilities in forested areas and coastlines, as in the case of the Akkuyu NPP. According to these provisions, the State is obliged to take into account the public interest and the protection of these natural assets during the development of nuclear projects. Plans that do not comply with these considerations, particularly in terms of public interest and protection of forests, face legal obstacles.

Similarly, the process of expropriation of private property for nuclear projects is subject to constitutional

provisions on property rights (Article 35) and expropriation limits (Article 46)

1.3.2. International conventions to which Türkiye is a party

Türkiye is a signatory to some of the key international nuclear texts, highlighted by its membership of the IAEA and its adherence to the 1957 Charter of the Nuclear Energy Agency (NEA, originally established as the OEEC European Nuclear Energy Agency).

The Paris Convention of 1960 on Third Party Liability in the Field of Nuclear Energy; was opened for signature in 1960 in order to determine the insurance and legal liability against radioactive leakages that may be encountered while using nuclear energy among the member countries of the Nuclear Energy Agency, which was established within the Organization for Economic Cooperation in Europe, with a common legislation among all member countries and to ensure that this legislation works in harmony. Today, only member countries of the Organization for Economic Cooperation and Development (OECD) can become a party to this convention. Our country is among the drafting countries of the Convention. One of the objectives of the Convention is to determine legal liability against third parties in the aftermath of possible nuclear incidents and to ensure that this does not hinder the peaceful use of nuclear energy. The Convention limits the scope of action of the parties by including clear provisions in terms of location and subject matter. In this way, the operator of nuclear facilities, the transporter and transporter of nuclear material are held legally responsible. The content of the Convention has been expanded and regulated by the subsequent joint protocols. The 1964 Protocol Amending the Paris Convention was adopted on February 12, 1964 and entered into force on April 5, 1968. The Convention was amended by an additional protocol in 1982. The Protocol was adopted in Paris on November 16, 1982 and entered into force on January 21, 1986. 1964 Additional Protocol and 1982 Protocol

The Treaty on the Non-Proliferation of Nuclear Weapons is an international treaty whose purpose is to prevent the spread of nuclear weapons and weapons technology, promote cooperation in the peaceful uses of nuclear energy and advance the goal of nuclear disarmament. Designed to advance the goal of non-proliferation and as a confidence-building measure between States parties, the Treaty establishes a system of safeguards under the responsibility of the International Atomic Energy Agency (IAEA). The Treaty was opened for signature in 1968 and entered into force in 1970. It is an international treaty whose purpose is to prevent the spread of nuclear weapons and weapons technology, to promote cooperation in the peaceful uses of nuclear energy and to advance the goal of nuclear disarmament.

The Convention on the Physical Protection of Nuclear Material, as amended in 2005, is the principal international legal instrument in the field of nuclear safety adopted under the auspices of the International Atomic Energy Agency (IAEA). It was signed in Vienna on 26 October 1979 and entered into force on 8 February 1987. The Convention imposes a legal obligation on the parties to ensure the physical protection of nuclear material during international transportation. It also established a general framework for inter-state cooperation in the protection, recovery and return of stolen nuclear material. The 9/11 attacks and heightened security concerns sought to broaden the scope of the Convention, and the amended Convention was adopted on 8 July 2005 and entered into force on 8 May 2016. The Convention is currently signed by 164 countries.

The Convention on Nuclear Safety was opened for signature by countries on September 20, 1994. Its purpose is to set out the basic safety principles for ensuring and maintaining a high level of safety in onshore nuclear power plants. The activities carried out by the Contracting Parties regarding the improvement of nuclear safety are discussed at the NPP Review Meetings held every three years, and the countries prepare their national reports on whether they are in compliance with the provisions of the Convention before these meetings and submit them to the International Atomic Energy Agency. The national contact point for the Convention is the Nuclear Regulatory Authority. Türkiye signed the Convention on September 20, 1994 and made it a part of its domestic legislation on October 24, 1996.

The Convention on Early Notification of a Nuclear Accident, adopted in 1986 following the Chernobyl Nuclear Power Plant accident, establishes a notification system for nuclear accidents in which a release of radioactive material has occurred or is likely to occur and which has resulted or may result in a transboundary release that may be of radiological safety significance to another State. The Convention requires states to report the time, place and nature of the accident and other data necessary to assess the circumstances of the accident. According to the provisions of the convention, notification to states affected by a nuclear accident is mandatory. Türkiye signed the convention in 1986 and made it part of its domestic law in 1991.

"The Convention on Assistance in the Event of a Nuclear Accident or Radiological Emergency was adopted on November 18, 1986 following the Chernobyl Nuclear Power Plant accident. It establishes an international framework for cooperation between States Parties and with the International Atomic Energy Agency (IAEA) to facilitate emergency assistance and support in the event of a nuclear accident or radiological emergency. The Convention requires states to notify the IAEA of their available experts, equipment and supplies to provide assistance. In the event of a request, each state party has the right to decide whether it can provide the requested assistance, its scope and conditions. Türkiye signed the convention in 1986 and it entered into force in 1991.

The Joint Protocol was adopted in 1988 to establish treaty relations between the Contracting Parties to the Vienna Convention and the Contracting Parties to the

Paris Convention and to eliminate conflicts that may arise from the simultaneous application of both Conventions to the same nuclear incident.

The International Convention for the Suppression of Acts of Nuclear Terrorism covers a wide range of acts and possible targets, including nuclear power plants and reactors, threats and attempts to commit or participate in such crimes as accomplices, extradition or prosecution. It encourages States to cooperate in preventing terrorist attacks by sharing information and assisting each other in connection with criminal investigations and extradition, and deals with crisis situations by helping States resolve post-crisis situations by securing nuclear material through the International Atomic Energy Agency. Türkiye signed the Convention in 2005 and it entered into force in 2012.

The Joint Convention on the Safety of Spent Fuel Management and Radioactive Fuel Management is the first legal instrument to address the safety of spent fuel and radioactive waste management on a global scale, and does so by establishing basic safety principles and through "peer review" similar to the Convention on Nuclear Safety. The Convention applies to spent fuel from the operation of civil nuclear reactors and radioactive waste from civil applications. It also covers planned and controlled releases of liquid or gaseous radioactive materials from regulated nuclear facilities into the environment. Türkiye signed the Unified Convention on 6 October 2021 and it entered into force on 21 May 2023.

1.3.3. Situation in Turkish laws

The 'Nuclear Regulation Law' No. 7282, which came into force on March 8, 2022, came into force during the period when the first reactor of Akkuyu NPP was about to be completed. This Law, which is the most comprehensive law in the history of Turkish nuclear regulation, defines their roles and powers regarding the use of nuclear energy and ionizing radiation. Again, in accordance with the international agreements signed by Türkiye, it requires compliance with international nuclear safety measures that require nuclear activities to benefit society or individuals (Kahraman, 2019), reduce radiation to the lowest possible level and keep exposure below thresholds. The law in question also oversees nuclear safety and safeguards.

The Nuclear Regulatory Law establishes a regulatory framework for nuclear activities by distinguishing between activities that require permits, licenses or permits, and activities that simply need to report. The law requires licenses for a wide range of nuclear power plant operations, from site preparation to decommissioning, as well as the import, export and transit of nuclear material.

The Nuclear Regulatory Law sets out detailed rules on radioactive liability and makes reference to the Paris Convention on Nuclear Liability in areas not covered by the Law. It establishes absolute liability for damages on nuclear operators, regardless of errors, personnel actions or technology defects, with liability caps in Euros of 700 million for nuclear power plants and 70 million for smaller plants. It requires operators to compulsorily insure their activities or to provide adequate coverage. The law allows the creation of a nuclear insurance pool financed by operators to cover nuclear-related damages, and the pool and the responsible operator to jointly compensate accidents.

Post-nuclear incident damage assessments are carried out by the 'Nuclear Damage Assessment Commission', appointed by the President, which compensates damages and requests reimbursement from operators and insurers. The law imposes criminal and administrative sanctions, including imprisonment for up to eight years and fines for unlicensed activity.

Regulations regarding nuclear energy and radioactive activities contain scattered provisions. Some provisions of previous nuclear laws have not been repealed. Among these, there are articles in the Law No. 5710 on the 'Construction, Operation and Energy Sales of Nuclear Power Plants'. According to the mentioned articles, the possibility of competitive tendering by TETAŞ (now EÜAŞ) is summarized in Article 3. In addition, Law No. 5710 stipulates that nuclear power plants built through competitive tendering can receive state aid. Finally, article 6/10 of the 'Electricity Market Law No. 6446' obliges nuclear power plant operators to apply to EMRA for an electricity generation license. This application must include preliminary permits from other authorities such as NDK for site development and reactor construction.

The regulatory disorganization of Türkiye's nuclear activities indicates that a regulatory framework is still in the formation stage. Monitoring the development of this regulatory area and ensuring compliance with constitutional and international laws are important for maintaining the legality and effectiveness of nuclear governance in Türkiye.

Due to the recent development of nuclear laws and the specific nature of projects such as the Akkuyu NPP, which are based on an international agreement and potentially exceed Article 90/Article 90, no significant cases of conflicts between national and international nuclear regulations have arisen in Türkiye. To date, many lawsuits have been filed against the Akkuyu NPP project and have been heard in the administration, regional administration and the Council of State. The arguments presented in these cases include allegations of fundamental constitutional violations, such as violation of the right to a healthy environment, and allegations of invalid environmental impact assessments or noncompliance with the Zoning Code. Despite this legal procedure, no nuclear project has been stopped or interrupted in Türkiye.

In light of all these scattered regulations and discussions, it can be suggested that Nuclear Law should emerge as a separate field of legal expertise and academic discussion. It is important to examine international law, specific demands of the energy private sector and environmental

risk issues. It is also necessary to expect the development of jurisprudence and administrative practices regarding nuclear activities in Türkiye through legal disputes in the long term.

2. Material and Method

Nuclear energy has become an important technology for scientific research, industry, agriculture, medicine and electrical energy production. However, in this regard, the peaceful use of nuclear energy has also strengthened the perception that it could lead to the spread of nuclear weapons and possible nuclear war. Therefore, the use and development of nuclear energy for peaceful purposes has become the focus of the international community. For these reasons, the International Atomic Energy Agency (IAEA) has begun to act as an important factor.

The most important goal of the Agency is to ensure that nuclear energy is used for peace, health and world welfare. At this stage, states that do not have any nuclear energy programs should be informed about the benefits and costs of this energy; It is very important that states with advanced nuclear energy programs should use nuclear energy in line with the rules of international law - especially safety and responsibility - with sustainable business management and technological developments based on international experience.

In order to measure Türkiye's compliance with the use of nuclear energy for peaceful purposes, the headings in international regulations are first examined as criteria:

A. Radiation protection

B. Nuclear and radiation safety

C. Nuclear liability

D. Nuclear security

To briefly explain the principles;

Radiation protection; radiation protection is the activities carried out to minimize the risk of radiation exposure to the public and the environment. These activities must prevent radiation from causing negative consequences. In order to be protected from radiation emitted as a result of a nuclear accident or in an uncontrolled manner, states that use nuclear energy must first take the necessary precautions in their domestic law. In other words, regulations regarding radiation protection must be foreseen in the domestic law of the country operating in this field. These regulations may include provisions such as determining any activity or facility that requires a license, authorizing the operator and determining the conditions for obtaining a license. Early Notification Convention in Case of Nuclear Accident and Assistance Convention in Case of Nuclear Accident or Radiological Emergency can be cited as examples of international regulations made in this field. In the aforementioned Conventions, it was emphasized that an international framework should be established to prevent nuclear accidents, minimize the consequences of nuclear accidents, and facilitate the rapid provision of assistance in the event of a nuclear accident or radiological emergency.

Nuclear and radiation safety; many of the expert opinions emphasized that the use of nuclear energy and ionizing radiation applications are the primary conditions for safety. According to the definition of the International Atomic Energy Agency, “nuclear and radiation safety means protecting workers, the public and the environment from the danger of unnecessary radiation, and providing appropriate working conditions to prevent accidents or mitigate the consequences of accidents.” (IAEA Safety Standards, 2015).

Nuclear liability; nuclear liability envisages compensation for damages arising from such accidents by developing regional and international legal regimes. Today, many regional and international agreements regulate nuclear liability.

Nuclear security; nuclear security is the most important factor regulating the legal framework of peaceful nuclear energy. The most important goal of nuclear security is to control the spread of sensitive nuclear technologies. The first and most important step to be taken to achieve this goal is to envisage legal regulations and mechanisms that will prevent the transfer of sensitive technologies in question.

Determining how much Türkiye includes these principles in its current laws will also determine how ready it is. In the evaluation, a five-point scoring table, which is a technique previously used in various articles in international publications, was used. [Aydın Coşkun and Gençay 2011), (Elvan and Türker 2014), (Elvan and Birben 2021)] peaceful use criteria were evaluated in order to evaluate its compatibility in Türkiye's legal system and management practices.

For this purpose, in the study, for each principle determined by the International Atomic Energy Agency for the peaceful use of nuclear in Turkish legislation, laws directly related to that principle in Türkiye, primarily the Constitution, were determined and the extent to which they were included in these laws was investigated. The following scoring system was used for this.

Scoring is made on a scale from 0 to 4:

0 = no provision or application;

1 = contains too narrow provisions or is impractical and inadequate;

2 = Contains an indirect provision or application but is not sufficient;

3 = Positive, indirect content is provided or applied and is sufficient;

4 = Positive, contains a direct provision or application and is sufficient

Each principle has been evaluated separately within the framework of the principles determined above. It will be determined that Turkish Legislation is sufficient in terms of principles with an average score above "2". The evaluation is made by taking into account the purpose and content of the constitution and relevant laws.

3. Results

The four criteria determined for the peaceful use of

Nuclear Energy are the Constitution and the Nuclear Regulation Law, as well as the Law No. 5710 on the Construction, Operation and Energy Sales of Nuclear Power Plants, which is still in force, the Law on Exemptions of the Turkish Atomic Energy Authority and Making Some Regulations, the Electricity Market Law, Law on Preventing the Financing of the Proliferation of Weapons of Mass Destruction, Law on Preventing the Financing of Terrorism, Law on the Supervision of Industrial Establishments Producing War Equipment and Equipment, Weapons, Ammunition and Explosives, Law on the Principles Applicable to Explosives and Suspicious Objects Seen in the Seas and on the Surface of the Country.

Law on Military Restricted Zones and Security Zones, Law on the Operation of Boron Salts, Trona and Asphaltite Mines and Nuclear Energy Raw Materials, Return of Some Lignite and Iron Fields, Law on the Establishment and Operation of Electrical Energy Production Facilities with Build-Operate Model and Regulation of Energy Sales, Investments No separate evaluation will be made for Project-Based Support and the Law on Amendments to Certain Laws and Decree Laws, the Turkish Civil Aviation Law, the Turkish Penal Code, the Turkish Commercial Code, the Insurance Law, the Mining Law, as well as the relevant regulations and circulars.

Scoring is done by taking into account the purpose of the law and the articles in its content.

Table 1. Place of criteria for peaceful use of nuclear energy in Turkish legislation

	A	B	C	D
1982 Constitution	1	1	1	1
Nuclear Regulatory Law	4	4	4	4
Law on the Construction, Operation and Energy Sales of Nuclear Power Plants	2	2	2	2
Law on Exemptions and Certain Regulations of the Turkish Atomic Energy Authority	2	2	2	2
Electricity Market Law	2	2	2	2

Table 1. Place of criteria for peaceful use of nuclear energy in Turkish legislation (continuing)

	A	B	C	D
Law on Preventing the Financing of the Proliferation of Weapons of Mass Destruction	2	2	2	2
Law on Prevention of Financing of Terrorism	1	1	2	3
Law on the Inspection of Industrial Establishments Producing War Vehicles and Equipment, Weapons, Ammunition and Explosives	1	1	2	4
Law Concerning the Principles Applicable to Explosive Substances and Suspicious Objects Seen in the Seas and on the Surface of the Country	2	4	2	4
Law on Military Restricted Zones and Security Zones	1	1	1	4
Law Regulating the Exploitation of Boron Salts, Trona and Asphaltite Mines and Nuclear Energy Raw Materials, and the Return of Some of the Lignite and Iron Fields	2	2	2	2
Law on the Establishment and Operation of Electrical Energy Production Facilities with the Build-Operate Model and the Regulation of Energy Sales	2	1	1	1

Table 1. Place of criteria for peaceful use of nuclear energy in Turkish legislation (continuing)

	A	B	C	D
Law on Supporting Investments on a Project Basis and Amending Certain Laws and Decree Laws	0	0	1	0
Turkish Civil Aviation Law	2	2	1	2
Turkish Penal Code	0	0	4	1
Turkish Commercial Code	1	0	3	0
Insurance Law	1	1	3	1
Mining Law	1	1	1	1

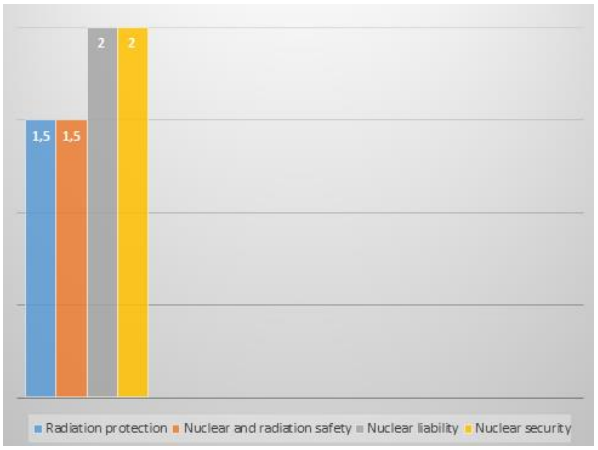

Figure 1. Legislation compliance chart for the peaceful use of nuclear energy in Türkiye.

According to Figure 1, it would be appropriate to consider those with an average score of 2 and above as adequate. When all laws related to the use of nuclear energy in force are examined, it is seen that the principles of Nuclear Liability and Nuclear Safety are sufficient.

Changes and developments should be made in the legislation for Radiation Protection and Nuclear Radiation Safety.

Regardless of all these evaluations, the Nuclear Regulation Law, which is our general law on nuclear energy, received 4 points on the basis of all principles and is positive, covers direct provisions, includes implementation and is sufficient. The Nuclear Regulation Law, which is a special law regarding the peaceful use of nuclear energy, fully carries the principles in question. The purpose of this law is, essentially, the principle of peaceful use, the principles and principles that should be aimed at protecting employees, the public, the environment and future generations from the possible harmful effects of ionizing radiation during the distribution of nuclear energy and ionizing radiation, and the responsibilities of the Nuclear Regulatory Authority, which has constant control over these activities. to determine the authorities and responsibilities and the legal liability for nuclear damage resulting from nuclear incidents. Therefore, it is possible to conclude that Turkish legislation is sufficient based on the general law regarding the peaceful use of nuclear energy.

4. Discussion and Conclusion

The use of nuclear energy in medicine, agriculture, consumer products, military vehicles, space studies, industry, scientific research, food safety, electricity and energy production is also essential on a technological basis.

The general opinion about nuclear energy in the world and in our country has developed towards the conservation of this energy. For this reason, international law defines the peaceful use of nuclear energy as an inalienable right of states. The IAEA Statute, review conferences, and provisions in bilateral security agreements concluded between the IAEA and other countries also reinforce the protection of this right. In this case, it is very important for states that use nuclear energy for peaceful purposes to operate this energy in accordance with the rules of nuclear law and to fulfill their obligations arising from the rules of nuclear law.

In accordance with Türkiye's energy policies, the desire to carry out more nuclear energy projects and gain technical expertise in this field continues. For this reason, Türkiye's legal framework regarding nuclear energy needs to undergo change and development. Closer alignment with international standards and monitoring the development of Turkish nuclear energy law, which will require increased international cooperation on a variety of issues, including safety measures, environmental protection, emergency response, nuclear fuel supply and radioactive waste management, will be a benefit not only for our country but also for the world in a globalizing economy. It becomes a duty. Türkiye is a party to all agreements regarding the use of nuclear energy for peaceful purposes and is open to inspections in this regard.

It is essential to evaluate the principles of peaceful use of nuclear energy established within the scope of international agreements. In this regard, prioritizing nuclear safety and taking appropriate measures to provide sufficient financial resources for this purpose; providing assurance that the requirements established for all activities in terms of safety of nuclear facilities are met; security assessment and verification, radiation protection, discussions with states located in the vicinity of sites selected for the construction of nuclear facilities and the possibility of examining the possible security effects of this facility on their territory; The place of the

principles of peaceful use in the Turkish Legal system, which includes compliance with national and international regulations during design and construction and operation, has been examined, and the evaluations for it within the scope of the Nuclear Regulation Law, which is our general law regarding nuclear energy in Turkish Legislation, are positive, include direct provisions, include implementation and are sufficient.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	N.V.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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Araştırma Makalesi (Research Article)
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AVLULARIN ESNEK KULLANIM POTANSİYELLERİ ÜZERİNE BİBLİYOMETRİK BİR ARAŞTIRMA

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Özet: Endüstri 4.0 ile ön plana çıkan bilişim teknolojilerinin neden olduğu değişimlere kentsel mekanların uyum sağlayarak sürdürülebilir hale gelmeleri önem kazanmıştır. Kentlerde yarı kamusal mekanlar olarak karşımıza çıkan avlular şehir dokusunda önemli açıklıkları oluşturmaktadır. Avluların gündelik yaşamda veya acil durumlarda birden çok amaca hizmet edebilecek şekilde esnek tasarlanması kentsel yaşamın kalitesinin ve bu mekanların canlılığının artmasına katkıda bulunacak böylece sürdürülebilir mekanlar haline gelecektir. Bu hipotezle yola çıkan araştırmanın amacı avluların esnek kullanım potansiyellerini soruşturmaktır. Çalışmada Web of Science (WoS) veri tabanında yapılan taramada elde edilen verilerin bibliyometrik analizi yapılmıştır. Bulgularda literatürdeki eğilimler ve eksiklikler analiz edilmiştir. Bu bağlamda avluların kentsel ölçekten çok yapı ölçeğinde ele alındığı, esneklik kavramının daha çok iklim değişikliğine uyarlanabilirlik olarak kullanıldığı ve yapay zekanın daha çok yöntem aşamasında kullanıldığı görülmüştür. Çalışmaların büyük bir kısmında kentsel ve gündelik yaşam, acil kullanımlar göz ardı edilmiştir.

Anahtar kelimeler: Avlu, Kamusal mekan, Yapay zeka, Esneklik

A Bibliometric Study on The Flexible Use Potentials of Courtyards

Abstract: It has become important for urban spaces to adapt to the changes caused by information technologies that have come to the fore with Industry 4.0 and to become sustainable. Courtyards, which appear as semi-public spaces in cities, constitute important openings in the urban fabric—designing courtyards flexibly so that they can serve multiple purposes in daily life or emergencies will contribute to the increase in the quality of urban life and the liveliness of these spaces, thus becoming sustainable. The aim of the research, which sets out with this hypothesis, is to investigate the flexible use potential of courtyards. In the study, bibliometric analysis of the data obtained from the Web of Science (WoS) database was performed. The trends and gaps in the literature were analyzed in the findings. In this context, it was seen that courtyards were addressed at the building scale rather than the urban scale, the concept of flexibility was used more as adaptability to climate change, and artificial intelligence was used more in the method stage. In most of the studies, urban and daily life, emergency uses were ignored.

Keywords: Courtyard, Public space, Artificial intelligence, Flexibility

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1. Giriş

Değişen ve sürekli değişme halinde olan yaşam, kentleşmenin de hızlı ve düzensiz olmasına neden olmuştur. Var olan boşlukların hızla doldurulduğu kentsel dokuda kentsel açık/yarı açık alanların oluşturduğu boşluklara ihtiyaç olduğu aşikârdır. Özellikle 2020 yılında tüm dünyayı etkisi altına alan Covid-19 pandemisi ve yangın, deprem gibi afetler kentte açık, nefes alan mekanlara ihtiyaç duyulduğunu göstermiştir. Bu durumda sayısı gün geçtikçe azalan kentsel boşlukların yalnızca açık mekan olarak değil hızla değişen dünyaya uyum sağlayabilen esnek mekanlar olarak tasarlanması da önem kazanmaktadır. Birden çok kentsel aktiviteye ve toplumsal ihtiyaca cevap verebilen mekanlar gündelik yaşamda kentliyle daha güçlü ilişki kurabilir. Avlular, gündelik yaşamda yapılı çevre içinde kamusal mekan ihtiyacına cevap veren boşluklar olarak kentsel dokuda önemli yer tutmaktadır. Kentsel avlular, şehirde kentsel mekan ve özel mekan arasındaki geçişi sağlayan yarı kamusal mekanlardır. İlk yerleşimlerden bu yana görülen avlular tarihte kent merkezi, pazar, kutsal mekan, toplanma alanı gibi birçok işlevi aynı anda barındırabilen esnek mekanlar olduğu görülmektedir. Açık ve yarı açık mekandan oluşan organizasyonu, kentsel açık alandaki kaostan uzaklaşabilen ancak aynı zamanda kamusal kullanımı sağlaması, güvenlik ve mahremiyet hissi sağlayabilmesi gibi özellikleri nedeniyle araştırma alanı olarak seçilmiştir. Çalışmada ele alınan hipotezler aşağıdaki gibidir:

- Kentsel açık mekanların esnek tasarlanarak gündelik yaşam ve acil durumlarda birden çok amaca hizmet vermesi mekanların sürdürülebilir olmasına katkı sağlar.
- Kentsel yarı açık mekanlar olarak avlular zengin mekan organizasyonu ve yarı kamusal özellikleri nedeniyle

esnek tasarlanma potansiyeli vardır.

Bu çalışmanın amacı kentsel avluların esnek kullanım potansiyellerini irdelemektir. Amaca koşut olarak günümüzde ön planda olan yapay zeka da bu araştırmalarda kullanım alanı ve kullanım potansiyelini de incelemek amacıyla araştırmaya dahil edilmiştir.

Kentsel açık mekanlarda esneklik literatürde birçok açıdan ele alınmıştır. Özellikle kullanıcı katılımını sağlamaya ve açık mekanların sürdürülebilir ve değişimlere adapte edilebilir tasarlanmasına yönelik birçok çalışma yer almaktadır: Sınmaz (2015), çalışmasında iletişim teknolojilerinin gelişmesinin kamusal mekanların kullanımı üzerindeki etkilerini konu edinmiş ve eğer değişen yaşam koşullarına uygun olarak esnek tasarlanmazsa kamusal mekanların anlamını kaybetme olasılığını vurgulamıştır. Alpak ve Düzenli (2018), çalışmalarında kentsel mekanın esnek-adapte edilebilir şekilde tasarlanmasına odaklanmış ve bu bağlamda meydan tasarım senaryoları kurgulamışlardır. Bayramoğlu ve Akıncı (2018) çalışmalarında peyzaj tasarımında boş alanların esnek-dönüşümlü mekanlar olarak tasarlanmasını ele almıştır. Benzer şekilde literatürdeki birçok çalışma kentsel açık mekanların esnek tasarlanmasının faydalarını hatta gerekliliklerini ortaya koymuştur: Toplumu oluşturan bireylerin birbirinden farklı gereksinimleri, teknolojik gelişmeler, sürekli değişen yaşam koşulları gibi değiştirilemez gerçekler kentsel mekanların esnek, birden çok amaca hizmet edebilir şekilde tasarlanmasını gerektirmektedir.

Kentsel açık mekanların esnek tasarlanması literatürde farklı açılardan ele alınmıştır: Nasıl esnek tasarlanması gerektiğine dair model ve tasarım önerisi yöntemiyle inceleyen çalışmaların (Marcus ve Francis, 1997; Gaucher, 2018; Sanei ve ark., 2018) yanında, sürdürülebilirlik (iklim değişimine adapte edilebilirlik), yeşil alan tasarımı (Gazel, 2022), su ögelerinin kullanımı gibi birçok parametre ile çeşitlendiği görülmektedir.

Özellikle dünyayı etkisi altına alan Covid 19 pandemisi ile açık alana artan ihtiyaç, kamusal açık alanların tasarımını tekrar ele almayı gerektirmiş ve birçok araştırmaya konu olmuştur. Bu araştırmaların büyük bir kısmında açık alanların esnek tasarlanması gerekliliğinin vurgulandığı görülmektedir (Sepe, 2021; Doostvandi ve ark., 2022; Özdede ve ark., 2021).

Türkiye'de 6 Şubat 2023 tarihinde meydana gelen depremin bir kez daha gösterdiği gibi doğal afet gibi acil durumlarda kentsel açık mekanların kullanımının önemi büyüktür. Bu nedenle acil durumlar sonrası ortaya çıkan geçici barınma, beslenme, korunma gibi temel ihtiyaçların bu mekanlarda sağlıklı bir şekilde sağlanması için bu mekanların tasarımının birden çok işleve hizmet edebilir şekilde esnek olması gerektiğine değinen çalışmalar (Gebel ve ark., 2023) görülmektedir.

Literatürde avluların zengin mekânsal organizasyonundan ve birden çok işleve olanak sağlayabilmesine değinen kaynaklar olsa da doğrudan esnek kullanım potansiyellerini irdeleyen bir çalışmaya rastlanmamıştır. Ayrıca bu çalışmaların büyük bir kısmının konutlar bağlamında olduğu görülmektedir: Çalışmalarda konut avlularının mekânsal önemi avlunun konut mekanlarına birbirinden farklı işlevlerle hizmet vermesi ile vurgulanmıştır (İslamoğlu ve Usta, 2017; Çolakoğlu, 2023). Ancak tüm bu çalışmalar, geçmişten örnek verme ya da halihazırda var olan esnek kullanımları belgelemenin ötesine geçmemiştir. Ayrıca avlunun kamusal kimliği büyük ölçüde göz ardı edilmiştir.

Altıparmakoğlu ve Gürani (2016) ise avluları eğitim yapıları üzerinden ele almış; çalışmada seçilen halihazırda var olan örneklerde avluların eğitim yapılarına katkıları değerlendirilmiştir. Shan (2016) tezinde modern avluların geleneksel avlulardan tamamen uzaklaşmadan ve değerlerini kaybetmeden tasarlanmasını ele almış ve avluların esnek tasarlanması gerektiğine sıklıkla değinmiştir.

Görüldüğü üzere kentsel mekanlarda esneklik çalışmaları çok çeşitli iken avlular gibi yarı kamusal olarak nitelendirilen mekanların sürdürülebilirlik açısından avantajlarının yanında gündelik yaşamda birden çok işlev ile kullanılma potansiyelleri ile ilgilenen oldukça az sayıda çalışma yer almaktadır. Ayrıca yapay zekanın esnek tasarım alanında kullanım potansiyellerine değinen bir başka çalışmaya rastlanmamıştır. Bu nedenle çalışma literatürdeki boşluklara ve potansiyellere odaklanmakta ve bibliyometrik analiz yöntemi ile hipotezleri araştırmaktadır. Kentsel mekan veya avluların esnek kullanım potansiyellerini araştıran bibliyometrik bir çalışmanın literatürde yer almaması da çalışmayı özgün kılmaktadır. Geniş kapsamlı bir literatür analizinin gelecekteki birçok çalışmaya ışık tutacağı düşünülmektedir.

2. Materyal ve Yöntem

Araştırmada belirlenen problem ve amaca yönelik bibliyometrik analiz yöntemi uygulanmıştır. Bu yöntemle literatürde kentsel mekan olarak avluların esnek kullanımına yönelik araştırmaları görmek ve literatürdeki boşlukları ya da yönelimleri saptayarak gelecekteki araştırmalara ışık tutmak amaçlanmıştır.

Literatür taraması için multidisipliner araştırmalara erişim sağlayabilen Web of Science (WoS) veri tabanı kullanılmıştır. Öncelikle avlularda esneklik ve yapay zeka üzerine yapılan çalışmaları taramak adına "avlu", "esneklik" ve "yapay zeka" anahtar kelimeleri belirlenmiştir. Bu kelimelerle yapılan taramada oldukça az veriye ulaşılması nedeniyle çalışmaya üst ölçekten bakmak gerekli olmuş ve kentsel mekanda yapılan çalışmalar da literatür taramasına eklenmiştir. Böylece avluların önemli bir parçası olduğu kentsel mekanlarda yapılan çalışmaların hangi alanlara odaklandığı, hangi problemleri tartıştığı anlaşılması hedeflenmiştir.

WoS veri tabanında tarama Tablo 1'de verilen araştırma soruları doğrultusunda belirlenen anahtar kelimeler ile yapılmıştır: "kentsel mekan", "avlu", "esneklik" ve "yapay zeka". "Kentsel mekan" ve "avlu" genel ve özel araştırma alanlarını, çalışmanın odaklandığı konu olan "esneklik"

bu mekanların esneklik potansiyellerini, "yapay zeka" bu mekanlarda yapılan esneklik çalışmalarının günümüz teknolojisi ile ilişkisini belirlemek amacıyla seçilmiştir.

Tablo 1. Araştırma soruları ve anahtar kelimeler

Soru	Anahtar kelime
Kentsel/kamusal mekanlarda esneklik, uyarlanabilirlik kavramları çerçevesinde hangi çalışmalar yapılmıştır?	kentsel mekan + esneklik
Kentsel/kamusal mekanlarda esnek kullanım üzerine yapay zeka araçlarından faydalanılarak yapılan araştırmalar var mıdır? Sorularına yanıt aranmıştır.	kentsel mekan + esneklik + yapay zeka
Avlularda esneklik, uyarlanabilirlik kavramları çerçevesinde hangi çalışmalar yapılmıştır?	avlu + esneklik
Avlularda esnek kullanım üzerine yapay zeka araçlarından faydalanılarak yapılan araştırmalar var mıdır? Sorularına yanıt aranmıştır.	avlu + esneklik + yapay zeka

WoS veri tabanında yapılan gelişmiş arama (advanched search) sırasında her bir sözcük öbeğinin çalışmalarda geçen/geçebilecek ilişkili kelimelere de "or" ifadesiyle yer verilerek araştırmanın zenginleştirilmesi hedeflenmiştir (Tablo 2). Örneğin esneklik kavramı "esnek kullanım", "esnek tasarım", "uyarlanabilirlik" gibi sözcüklerle genişletilmiştir. "Kentsel mekan" kavramı ise araştırmanın daha iyi odak oluşturması amacıyla "kamusal mekan" kavramıyla desteklenmiştir.

Taramalar "kentsel mekan" ve "avlu" anahtar kelimeleri ile olmak üzere iki ana aşamada gerçekleştirilmiştir. Bu iki kelime ayrı ayrı diğer anahtar kelimeler ile kombinasyonlar halinde incelenmiştir. Böylece literatürde kentsel mekanlar ile avlular üzerine yapılan çalışmaların karşılaştırılabilmesi hedeflenmiştir. Bu durum ayrıca kentsel mekanda yapılan çalışmalarda tespit edilen boşlukların ya da potansiyellerin avlu üzerine yapılan çalışmalarda da göz önünde bulundurabilmeyi sağlayacaktır. "Kentsel mekan" ve "avlu" kelimeleri sırasıyla "esneklik" ve "esneklik + yapay zeka" kelimeleri ile arama yapılmış: Böylece önce mekanların (kentsel mekan ya da avlu) esneklik ile nasıl bir ilişkide olduğu sonrasında ise bu esneklik araştırmasına yapay zekanın katılımının nasıl ele alındığı incelenmiştir.

Taramalarda elde edilen yayınlarda konu dışında kalan çalışmaları kapsam dışı bırakabilmek adına mimari ve kentsel disiplinler seçilerek filtrelenmiştir. Böylece hem mimari ve kentsel alanlarda hem de diğer alanlarda yapılan çalışmaların karşılaştırılması mümkün olmuştur. Taramalar sonucunda elde edilen verilerin öncelikle açık kaynak kodlu RStudio Version 4.3.3 programı ve bir R program aracı olan "biblioshiny for bibliometrix" uygulaması (Aria ve Cuccurullo, 2017) ile analizi yapılmış ve nicel veriler elde edilmiştir. Böylece her bir taramanın anahtar kelime, yıllara göre yayın sayısı grafiği gibi yorumlanabilecek verileri elde edilmiştir. Sonrasında yapılan her bir taramada en çok atıf alan ikişer yayın detaylı olarak incelenmiştir.

Tablo 2. Veri tabanında kullanılan anahtar kelimeler*

Anahtar Kelimeler	Sözcük Öbekleri	Kod
Kentsel Mekan	urban space public space urban public space urban place public place urban public place	"urban space" OR "public space" OR "urban public space" OR "urban place" OR "public place" OR "urban public place"
Esneklik	flexible use flexibility flexible space urban resilience resilience elasticity adaptive adaptive use adaptability adaption	"flexible use" OR "flexible design" or "flexibility" OR "flexible place" OR "flexible space" OR "elasticity" OR "resilience" or "urban resilience" or "adaptive" OR "adaptive use" OR "adaptability" OR "adaptation"
Yapay Zeka	artificial intelligence deep learning machine learning generative artificial intelligence generative ai artificial neural networks	"artificial intelligence" OR "deep learning" OR "machine learning" OR "generative artificial intelligence" OR "generative ai" OR "natural language processing" OR "artificial neural networks"
Avlu	courtyard Urban courtyard Urban space courtyard	"courtyard" OR "urban courtyard" OR "urban space courtyard"

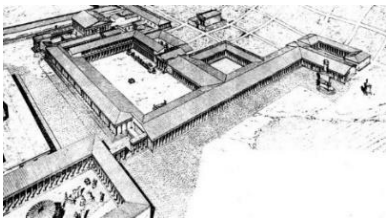
*WoS veri tabanının dili ingilizce olduğundan tablodaki kelimeler orijinal dilinde verilmiştir.

2.1. Literatür Araştırması

Bir kentte kamusal alanlar yollar, parklar, meydanlar gibi herkese açık mekanlar iken özel mekanlar, belirli kişilerin mülkiyetinde olan konut yapıları ve konutlara özel tasarlanan açık alanlardır. Yarı özel mekanlar sadece belirli kişilerin girebileceği mekanlardır. Yarı kamusal mekânlar ise toplumun belirli bir kesiminin belirli zamanlarda kullanılacağı konut önündeki açık alanları, kaldırımları, çıkmaz sokakları, açık bir avluyu ve benzeri toplumsal mekânları kapsamaktadır. Yarı özel ve yarı kamusal mekanlar; özel ve kamusal mekanlar arasında keskin sınırlar oluşmasını engeller ve geçiş mekanı niteliği taşırlar. Böylece kentsel mekan hiyerarşisi kurulmuş olur ve kentin okunabilirliği artar (Sınmaz,

2018).

Literatürde "avlu" kavramının birçok tanımı yer almaktadır. Avlu, çevresi yapı ya da duvar gibi yapısal ögelerle sınırlandırılmış ve böylece iç ve dış mekan arasında geçişi sağlayan yarı açık mekanlar olarak tanımlanabilir. Avlular özel mekanlar ile kentsel mekanı bağlayan arayüz mekanları olmaları nedeniyle yarı-kamusal mekan niteliğindedir. Kent ve özel mekanlar arasındaki geçiş mekanları olan avlular kentsel dış mekandan soyutlanmaya ve doğal unsurların yer aldığı özel alanlar oluşturmaya uygun mekanlardır. Sağladıkları sosyal ve kültürel bir açık/yarı açık mekan ile kendisini çevreleyen binaların işlevlerini tamamlayarak binaların kent ile ilişkisini kurarlar (Erdoğan, 1996). Avluların içe dönük gibi görünen mekan kurgusu avluların pasif etkinlik alanları olduğu algısını yaratsa da aslında kentliye birçok etkinlik imkanı sunan kentsel rekreasyon alanlardır (Yoldaş, 2010). Geçmişten günümüze avlular ilk yerleşimlerden bu yana farklı formlarda, farklı işlevlerde kullanılan mekanlar olmuştur. İlk örneklerinde daha çok dış tehlikelerden korunma, güvenliği sağlama amaçları ön plana çıksa da (Aydın, 2000; Keister, 2005) zamanla hizmet ettiği işlevler artarak ve çeşitlenerek gündelik yaşamın çok önemli bir unsuru haline gelmiştir. Konut yerleşimlerinin yanı sıra daha büyük ölçekte kente hizmet eden toplanma alanı niteliğinde avlular da görülmektedir. Geçmişten günümüze yapı veya kentlerde odak noktası, kutsal, ticaret alanı (Pazar), yönetim gibi işlevlerin hepsini veya birkaçını bir arada üstlenen yarı açık mekanlar olmuştur (Şekil 1 ve 2) (Yoldaş, 2010).



Şekil 1. Antik Yunan döneminde agora, Milet (Kleiner, 1968).

Şekil 2. Beyazıt Cami avlusu (Demirel ve Pilehvarian, 2018).

Çoğunlukla dini ve yönetim yapıları ile ilişkilenen avluların kimi örneklerinde korunma, güvenlik (Keister, 2005), mahremiyet (Schoenauer ve Seeman, 1962; Abass ve ark., 2016) gibi işlevlerini de devam ettirdiği görülmektedir. İklim, avluların oluşumunda oldukça önemli bir rol oynamakta; güneş ve rüzgar yönüne göre doğru yönlendirilerek (Meir ve ark. 1995; Abass ve ark., 2016) ve kullanılan su, yeşil ögeler gibi doğal unsurlarla tasarlandığında termal konfor sağlayan mekanlardır (Almhafdy ve ark., 2013; Abass ve ark., 2016). Tarih boyunca avluların plan organizasyonundaki yeri (yan, ön, orta, iç gibi), binalarla ilişkisi, avluda yer alan elemanlar (zemin döşemesi, yeşil alan, su ögesi gibi) bulunduğu yörenin iklimi, kültürü, üretim şekli gibi etkenlerle şekillenmiştir (Erdoğan, 1996). Kentsel dokuda avlular; insan, çevre ve binalar arasındaki dengeyi hem form hem de işlevsel olarak sağlamaktadır. Kentlilerin bir araya gelerek pasif ve aktif aktivitelerde bulunarak iletişimde olmalarını sağlamaktadır (Gül ve Küçük, 2001). Özetle avlular tarih boyunca dini, kamusal, siyasi, ticaret gibi işlevleri aynı anda barındırabilen çok işlevli yarı kamusal mekanlar olmuştur. Çevresindeki yapılara veya toplumun ona yüklediği işlevlere ek olarak gündelik yaşamın önemli bir parçası olmuş, sosyal ve kültürel ilişkilerin kurulduğu toplanma alanları olmuştur.

Toplum ve kentin diyalektik ilişkisinde sürekli bir değişim söz konusudur: Bu sürekli değişen yaşam koşullarına mekanların uyum sağlaması zorunludur. Esnek tasarım, mekanların değişen çevre, teknoloji ve işlevlere uyum göstererek yıkımdan kurtulmasını sağlar. Özellikle iklim krizi bilinciyle sürdürülebilirlik kavramının ön plana çıktığı günümüzde esneklik çağdaş mekanların vazgeçilmez bir tasarım kriteri haline gelmiştir (İslamoğlu ve Usta, 2018). Açık mekân tasarımında esnek ya da uyarlanabilir tasarım, toplumu oluşturan birbirinden demografik, sosyal ve kültürel alanlarda ayrılan bireylerin isteklerine göre çok boyutlu yaklaşımla yapılmalıdır: Bu bireylere istekleri doğrultusunda konum değiştirebilme ve kendine ait kısa süreli yerler yaratabilme imkanı sağlamalıdır. Böylece birbirinden farklı etkinliklere uygun, isteğe bağlı olarak farklı etkinlik alanlarına dönüştürülebilen esnek mekanlar ortaya çıkar (Alpak ve Düzenli, 2018). Alpak ve Düzenli (2018) esnek kentsel mekanların insanların planlı ya da plansız bir şekilde bir araya gelmesini ve toplanmasını sağlayarak hem kentsel mekanın canlılığına katkı sağlayacağını hem de sosyal ve kültürel ilişkileri besleyeceğini belirtmiştir.

Esnek tasarım yalnızca kentsel mekanların kalitesini ya da canlılığına katkı sağlama amacına hizmet etmemekte aynı zamanda olası afet, salgın gibi olumsuz koşullara dayanıklı kentsel mekanlar oluşturmayı da hedefleyebilmektedir. Nitekim geçtiğimiz yıllarda dünyada ve ülkemizde önemli kırılma noktaları meydana gelmiştir. Bunlardan biri 2020 yılında tüm dünyayı sarsan Covid-19 pandemisidir: Salgının bulaşma tehlikesinin yanında yaşamda getirdiği yasak ve sınırlılıklar kentsel açık mekanların önemini bir kez daha vurgulamıştır. Aynı zamanda gündelik yaşamda meydana getirdiği değişimler mekanlara da yansımıştır. Pandemi dönemi de mekânsal esnekliğin daha fazla önem kazandığı, olası mekânların kullanım hacminin değişimine olanak tanıyan esnek mekân kullanımını yaşantımıza dahil etmiştir (Durmuş ve Asımgil, 2021). 6

Şubat tarihinde meydana gelen deprem de ülkemiz için kentsel açık alanların önemini tekrar hatırlatan bir kırılma noktası olmuştur. Yeri ve zamanı öngörülemeyen afet durumlarında kuşkusuz en önemli önlem afetlere hazırlıklı olmanın önemi acı bir şekilde tekrar gündeme gelmiştir. Acil durumlarda tahliye, geçici barınma gibi işlevlerde kullanılabilecek kentsel boşlukların günümüz kentlerinde hızlı kentleşmenin etkisiyle azalması, hatta yok olması başka potansiyel mekânlar bulma arayışını ortaya çıkarmaktadır (Zengin ve ark., 2017). Nitekim kentsel açık/yarı açık alanların afet durumlarında kullanıma da uygun olacak şekilde planlanması son dönemde öne çıkan konulardandır.

21. Yüzyılın başından itibaren hızla gelişmeye devam eden teknolojik gelişmeler yeni bir sanayi devrimine yol açmıştır: Endüstri 4.0'da yeni üretim modelinde temel üretim gücü yaratıcı ve yenilikçi bilgi, ham madde ise bilişsel güçtür. Üretimde verimlilik emek ya da makine gücüne değil zihin gücü ve yaratıcı akıl ile ölçülmektedir. Tüm bu değişimler toplumun ihtiyaçlarının, yaşam standartlarının değişmesine neden olmuştur: İleri teknolojiler ihtiyaçların anlık ve sanal çözümlerini sağlayarak yarattığı dinamizm ile kentsel yaşamda sürekli hareket ve değişim getirmiştir. Efeoğlu ve Çalışkan (2019) bu yeni üretim şeklinin kentsel mekanda daha esnek, çoklu ve bütünleşik bir fiziksel mekâna yol açacağını öngörmüştür. Onlara göre yeni çağın getireceği dinamizm ile kesin sınırları olan fonksiyonel bir mekânsal örüntüden çok kentsel çevre ile uyumlanabilir farklı tasarım alternatifleri ön plana çıkacak ve kentsel mekân sürekli ihtiyaca ve isteğe göre gelişebilir ve dönüşebilir olacaktır. Bu durum, daha bağdaşık ve bütünleşik mekânsal yapıların ortaya çıkmasına yol açabilir (Efeoğlu ve Çalışkan, 2019).

Endüstri 4.0 ile hayatımızın her alanına sızan "yapay zeka" problemlerin çözümü için sezgisel prensiplerle çalışan teknolojiler olarak tanımlanabilir. Amacı makinelerin bilinç sahibi canlılara benzer bir şekilde karar alma, veriler arası ilişki kurma, öğrenme, düşünme gibi yeteneklerini taklit etmesidir (Aksoylu, 2023). Yapay zekanın kentsel planlamanın ön tasarım, tasarım ve sonrasında da kullanılabildiği görülmektedir. Ön tasarım sürecinde dijital sensörler ve veri analiz araçları yardımıyla mevcut durum analizini yaparak sorunları ortaya çıkarır. Tasarım aşamasında hedef alanın mevcut verilerine göre tasarım seçenekleri oluşturmada kullanılır. Bu durum karar verme sürecini hızlandırır. Tasarımdan sonraki gözlem aşamasında ise kentsel alanın verimliliği ve işlevselliği zaman içinde gözlemlenir ve elde edilen veriler, makine öğrenimi algoritmalarını zenginleştirmek için kullanılabilir. Böylece kentsel alanı iyileştirmek için yapay zeka yardımıyla gelecekteki mekânsal müdahaleler yapılabilir (Ahmed, 2022). Görüldüğü üzere yapay zeka kentsel mekanlarda sınıflandırma, optimizasyon ve tasarım alternatifleri oluşturmanın yanında tasarımı gözlemleyerek müdahalede bulunabilen bir noktaya gelmiştir.

3. Bulgular

WoS veri tabanında araştırmanın amaç ve hedefine yönelik yapılan taramalarda elde edilen yayınların sayısal bilgisi Tablo 3'te verilmiştir. 1005 doküman arasında çalışma sayısının en fazla kentsel mekan ve esnek kullanım araştırmasında olduğu görülmektedir. Avlularda yapay zekanın dahil olduğu çalışmalar esnek kullanımın dahil olduğu çalışmalara göre daha az sayıdadır. Hem kentsel mekan hem de avlular ile esnek kullanım ve yapay zekanın bir arada yer aldığı çalışmalar literatürde oldukça az yer kaplamaktadır. Sonraki aşamada çalışmalar WoS veri tabanının kategorilerinde mimarlık ve kentsel çalışma disiplinlerindeki kategorilerine (Architecture, Regional Urban Planning ve Urban Studies) göre filtrelenmiştir (Tablo 3). Bu filtreleme ile 1005 doküman arasından 268 çalışmaya ulaşılmıştır. Araştırma sonuçları belirlenen kategorilere filtrelendiğinde çalışma sayılarında yüksek oranda azalma olduğu görülmüştür. Hem kentsel mekanda hem avlu mekanları ile yapay zeka ve esnek kullanımı aynı anda konu olarak işleyen çalışma literatürde yer almamaktadır. Burada kentsel disiplinlerde bir literatür açığı olduğu ortaya çıkmaktadır. Bu durumda analiz aşamasında çalışmada başka disiplinlerde yapılan çalışmaların da göz önünde bulundurulması gerekli olmuştur.

Tablo 3. Taramada elde edilen yayın türlerinin sayısal dağılımı

Anahtar kelimeler	Kategori yok	Kategori var (Architecture, Urban Studies, Regional Urban Planning)
Avlu + yapay zeka + esnek kullanım	2 makale	0
Kentsel mekan + esnek kullanım	649 çalışma (507 makale + 121 konferans + 19 kitap bölümü)	209 çalışma (157 makale + 42 konferans + 10 kitap bölümü)
Kentsel mekan + yapay zeka + esnek kullanım	8 çalışma (7 makale + 1 konferans)	0
avlu + esnek kullanım	117 çalışma (94 makale + 23 konferans)	23 çalışma (17 makale + 6 konferans)
Toplam	1005 (780 makale + 204 konferans + 19 kitap bölümü)	268 (206 makale + 52 konferans + 10 kitap bölümü)

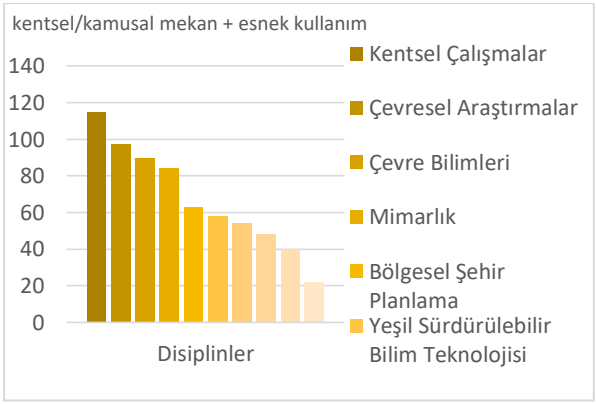
3.1. Kentsel/Kamusal Mekan Üzerine Yapılan Çalışmalar

3.1.1. Kentsel/kamusal mekan ve esnek kullanım üzerine yapılan çalışmalar

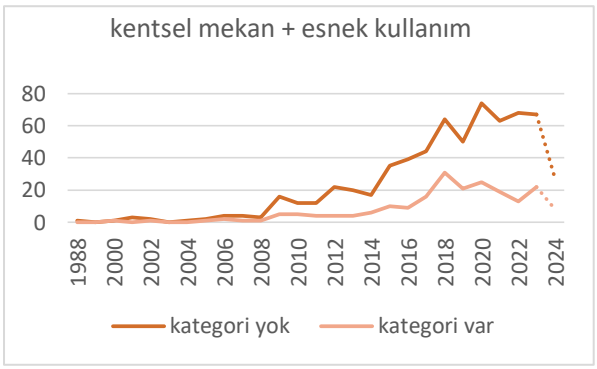
WoS veri tabanında "kentsel/kamusal mekan" ve "esnek kullanım" üzerine yapılmış çalışmalara ulaşmak amacıyla anahtar kelime olarak Tablo 2'de verilen "kentsel/kamusal alan" ve "esnek kullanım" kelime grupları girilerek tarama yapılmıştır. Arama sonucunda hiçbir filtreleme yapılmaksızın 649 çalışmaya erişilmiştir. 649 çalışmanın 509'u makale, 121'si sempozyum/konferans bildirileri ve 19'u kitap bölümüdür. WOS veri tabanında yapılan bu çalışmaların büyük bir kısmının kent, çevre ve mimarlık disiplinlerinde ele alındığı görülmektedir (Şekil 3). 649 çalışmanın 209'u bölge planlama, kentsel çalışmalar ve mimarlık disiplinlerinde yapılmıştır. Bu çalışmaların 157'sini makale, 42'sini konferans ve 10 tanesi kitap bölümü çalışmaları oluşturmaktadır.

Biblioshiny programı ile yapılan bibliyometrik analiz sonucunda ortaya çıkan yıllara göre üretilen yayın sayıları Şekil 4'teki grafikte verilmiştir. Disiplinlere göre filtreleme yapılmayan yayınların 2008 yılından itibaren sayıca artmaya başladığı görülürken; kentsel ve mimarlık alanlarında yapılan çalışmaların 2014 yılından itibaren artış gösterdiği görülmektedir. 2020 yılında ise her iki yayın grubunun sayısında düşme eğilimi olduğu gözlenmiştir.

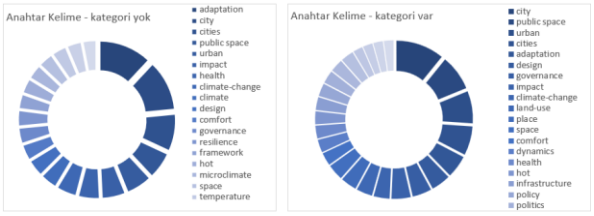
Anahtar kelimelerin kullanım sıklığı incelendiğinde kategori fark etmeksizin kentsel mekan, adaptasyon, kent, kamusal mekan ve iklim, sıcaklık, termal konfor gibi iklim değişimine vurgu yapan kelimelerin çoğunlukta olduğu görülmektedir (Şekil 5). Özellikle adaptasyon kelimesinin ön planda olduğu dikkat çekmektedir.



Şekil 3. Kentsel/kamusal mekanlar ve esnek kullanım üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı



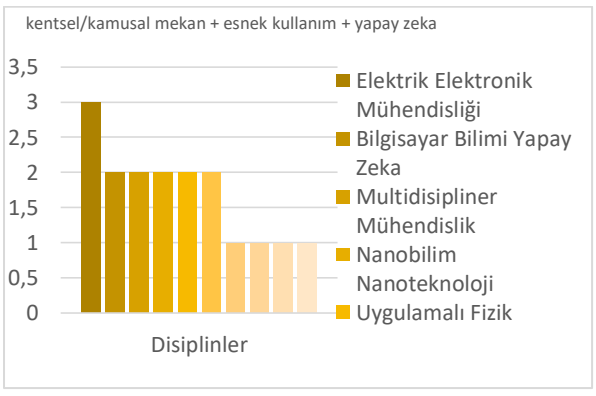
Şekil 4. Kentsel/kamusal mekanlarda esnek kullanım üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı



Şekil 5. Kategori olmadan (sol) ve kategorilere göre (sağ) yapılan taramaların anahtar kelime analizi

3.1.2. Kentsel/kamusal mekan, esnek kullanım ve yapay zeka üzerine yapılan çalışmalar

WOS veri tabanında kentsel/kamusal mekan, esnek kullanım ve yapay zeka üzerine yapılmış çalışmalara ulaşmak amacıyla anahtar kelime olarak Tablo 2'de verilen "kentsel/kamusal alan", "esnek kullanım" ve "yapay zeka" kelime grupları girilerek tarama yapılmıştır. Arama sonucunda hiçbir kategorizasyon yapılmaksızın 8 çalışmaya erişilmiştir. 8 çalışmanın 7'sı makale, 1'i sempozyum/konferans bildirisi türündedir. Çalışmaların arasında kentsel ve mimarlık alanında yapılmış bir çalışma yer almamaktadır (Şekil 6).

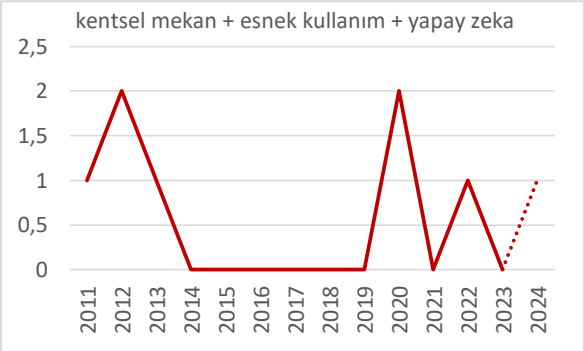


Şekil 6. Kentsel/kamusal mekanlar, esnek kullanım ve yapay zeka üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı

Çalışmaların yıllara göre üretim grafiği (Şekil 7) incelendiğinde 2011 yılında başlayan ve artış eğilimi gösteren çalışmaların 2013 yılından itibaren duraksadığı

görülmektedir. 2020 yılında tekrar yayın üretildiği görülse de henüz düzenli bir artış gözlenmemektedir. Ancak 2024 yılının ortasında bir yayının yapılmış olması da dikkat çekmektedir.

Çalışmaların Biblioshiny programı kullanılarak elde edilen anahtar kelime analizi (Şekil 8) incelendiğinde yalnızca dört kelime olduğu ve tüm kelimelerin eşit frekansta kullanıldığı görülmektedir. Kelimeler arasında "yaya tanıma (pedestrian recognition)" kelime grubu dikkat çekmektedir. Burada kentsel mekanda yayaların kentteki hareketi ve algısına yönelik çalışmalar olduğu çıkarımı yapılabilmektedir.



Şekil 7. Kentsel mekanlar, esneklik ve yapay zeka üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı

Şekil 8. Kelime bulutu analizi

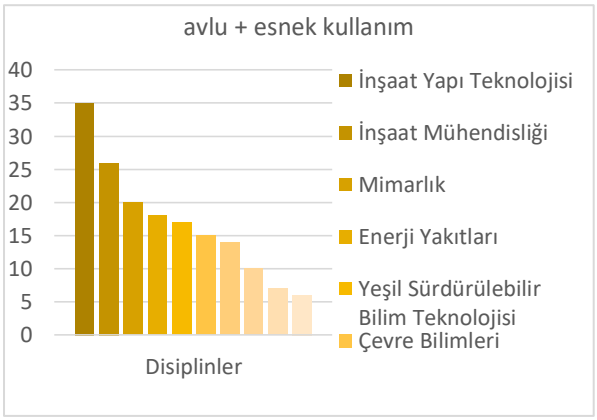
3.2. Avlular Üzerine Yapılan Çalışmalar

3.2.1. Avlu ve esnek kullanım üzerine yapılan çalışmalar

WoS veri tabanında avlu mekanları ve esnek kullanım üzerine yapılmış çalışmalara ulaşmak amacıyla Tablo 2'de verilen "avlu" ve "esnek kullanım" kelime grupları girilerek tarama yapılmıştır. Arama sonucunda hiçbir kategorizasyon yapılmaksızın 117 çalışmaya erişilmiştir. 117 çalışmanın 94'sı makale, 23'i sempozyum/konferans bildiri türünde yapılmıştır. Şekil 9'da görüldüğü üzere çalışmaların yapıldığı disiplinler incelendiğinde inşaat ve yapı odaklı disiplinler öne çıksa da mimarlık ve kentsel alanda çalışmaların da yer aldığı görülmektedir.

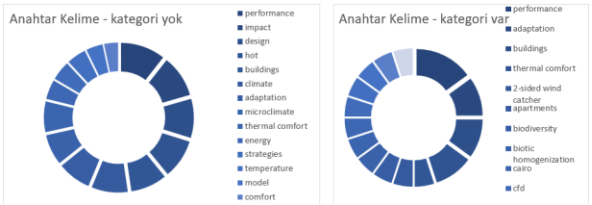
Avlu ve esnek kullanım üzerine ilk çalışma 1998 yılında yapılmış olsa da 2002-2007 yıllarında yayın üretimi olmamıştır (Şekil 10). Yayın üretimi tekrar 2008 yılında başlamıştır. Çeşitli dönemlerde yayın üretimi azalıp artsa da 2021 yılından itibaren düzenli artış göstermeye başlamıştır. Kent ve mimarlık disiplinlerinde yapılan çalışmalar ise 2009 yılında başlamıştır. Bu alanda en yüksek yayın üretimi 2022 yılında yapılmış ancak 2023 yılında hiçbir yayın üretilmemiştir.

Anahtar kelime analizi yapıldığında performans kelimesinin öne çıktığı görülmektedir (Şekil 11). Kelimelerin çoğunluğunun sürdürülebilirlik alanında kullanılan iklim, sıcaklık, termal konfor gibi kelimeler oluşturmaktadır. Ayrıca adaptasyon ve yapı kelimeleri de öne çıkmaktadır.



Şekil 9. Avlu ve esnek kullanım üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı

Şekil 10. Avlular ve esneklik üzerine yapılan çalışmaların sayılarının yıllara göre dağılımı



Şekil 11. Kategori olmadan (sol) ve kategorilere göre (sağ) yapılan taramaların anahtar kelime analizi

3.2.2. Avlu, Esnek Kullanım ve Yapay Zeka Üzerine Yapılan Çalışmalar

WoS veri tabanında makale türünde 2 çalışmaya erişilmiştir. Ulaşılan verilerin az sayıda olması nedeniyle aramada araştırma kategorileri, dil seçimi gibi filtreleme adımı uygulanmamıştır. 2 makalenin halihazırdaki WoS veri tabanında yer alan kategorileri "matematik" ve "robotik" kategorileridir (Tablo 4). Çalışmalardan en çok atıf alan çalışma 2024 yılında yapılmıştır. Matematik alanında yapılan çalışmada avlularda sıcaklık tahmini için yapay zekanın dallarından biri olan makine öğrenimi yöntemi kullanılmıştır. Robotik alanında yapılan çalışmada avlu yalnızca simülasyon deneyinin yapıldığı mekan çeşitlerinden biri olarak ele alınmıştır.

4. Tartışma

Bibliyometrik analiz aracılığıyla elde edilen sonuçlar genel hatlarıyla Tablo 5'te özetlenmiştir. Bu tabloda araştırmanın her aşaması için en çok kullanılan anahtar kelime, çalışmaların yer aldığı kategori ve çalışmaların yayınlandığı yıllarda kritik görülen yıllara yer verilmiştir. Çalışmanın "Bulgular" bölümünde verilen Tablo 3'te de görülebileceği üzere en çok sayıda çalışma kent ve esneklik üzerine yapılmıştır. Ayrıca Tablo 5'te görüldüğü üzere bu alandaki çalışmaların üretim tarihi diğerlerine göre daha öncedir. Avlu üzerine yapılan çalışmalarda da esneklik kavramının ele alındığı çalışmaların diğerlerine göre fazla sayıda olduğu görülmektedir. Bu durum esneklik kavramının kentsel mekanlarda uzun süredir ve sıklıkla ele alındığını göstermektedir.

Tablo 4. Avlularda esnek kullanım ve yapay zeka üzerine yapılan çalışmalar

Başlık	Yazar, yıl	Atıf	Kaynak	Anahtar Kelimeler	Konu
Applied Machine Learning Algorithms for Courtyards Thermal Patterns Accurate Prediction	Diz-Mellado ve ark., 2021	16	Mathematics	Courtyard, climate change, microclimate, Support Vector Regression (SVR), machine learning	Makine Öğrenimi ile avlularda sıcaklık tahmini yapılmıştır.
ASC: Adaptive Skill Coordination for Robotic Mobile Manipulation	Yokoyama ve ark., 2023	0	IEEE Robotıcs And Automatıon Letters	AI-enabled robotics, reinforcement learning, deep learning methods	Sanal olarak tasarlanmış iç mekanlarda eğitilen Uyarlanabilir Beceri Koordinasyonu (ASC) sekiz gerçek dünya ortamında (bir daire, bir laboratuvar, iki mikro mutfak, iki salon, bir ofis alanı ve bir dış avlu) test ederek karşılaştırma yapılmıştır.

Kentsel mekan, esneklik ve yapay zeka üzerine yapılan çalışmalar oldukça az sayıdadır ve mimari ve kentsel disiplinlerde herhangi bir çalışma yer almamaktadır. Anahtar kelimeler yalnızca dört tanedir ve tüm kelimelerin eşit frekansta kullanılmıştır. Kelimelerin çoğunluğunun yapay zeka ve veri işleme alanında kelimeler olduğu görülmektedir. Bu kelimelerin dışında "yaya tanıma" kelime grubu dikkat çekmektedir.

Avlu ve esneklik üzerine yapılan çalışmalarda performans kelimesi öne çıkmaktadır. "tasarım", "etki", "sıcaklık" ve "yapılar" kelimeleri bu alanda yapılan çalışmaların daha çok iklimsel ya da yapısal olduğuna işaret etmektedir. Mimari ve kentsel filtreleme yapıldığında ise anahtar kelimeler değişse de yine de ana temanın aynı olduğu aynı zamanda incelenen makalelerden de anlaşılmaktadır. Esneklik burada da uyarlanabilirlik kelimesi ile ele alınmıştır.

En az sayıda çalışma ise "avlu + esnek kullanım + yapay zeka" aramasında elde edilmiştir ancak burada günümüze en yakın tarihte üretilmeye başlanan çalışmalar vurgulamak gerekmektedir. Bu durum çalışma konusunun ilgi çekmekte olduğuna işaret etmektedir.

"Kentsel mekan + esneklik + yapay zeka" kavramlarının taranmasıyla elde edilen verilerde mimari ve kentsel disiplinlerde yapılmış bir çalışma yer almamaktadır. Diğer kategorilerde yapılan çalışmalara bakıldığında özellikle 2013-2019 yılları arasında üretimin hiç yapılmaması dikkat çekmektedir. 2020, 2022 ve 2024'te az sayıda yayın elde edildiği görülmektedir.

Kentsel mekan ve esneklik üzerine yapılan çalışmalarda "adaptation (uyarlanabilirlik)" kelimesinin öne çıktığı görülmektedir. İncelenen makalelerde de genellikle bu kelime ile karşılaşılmıştır. Ancak çalışmalarda iklim değişikliğine uyarlanabilirlik, farklı ortamlarda uygulanabilir modeller olarak kullanıldığı görülmüştür.

Tablo 6 ve 7'de çalışmada incelenen her kategoride en

çok atıf alan iki çalışma toplamda 12 çalışmanın künyesi ve problem, yöntem, alan gibi detaylı verileri sunulmuştur. Ayrıca araştırılan kavramların bu çalışmalarda hangi anlamda ele alındığı bilgisine yer verilmiştir.

Kent ve esneklik üzerine yapılan çalışmalardan biri kuramsal ve eleştirel yaklaşımla yazılırken diğeri finansallaşmanın kentsel mekandaki sosyolojik etkilerine odaklanmıştır. Her çalışmada da kentsel mekanın soyut ve toplumsal yönüne odaklanılmıştır. Esneklik kavramı ilk çalışmada otomobilin kentsel yaşama getirdiği esneklik olarak ele alınırken diğer çalışmada finansal stratejilerin uyarlanabilir olması anlamında kullanılmıştır.

Tablo 6 ve 7'de çalışmada incelenen her kategoride en çok atıf alan iki çalışma toplamda 12 çalışmanın künyesi ve problem, yöntem, alan (varsa) gibi detaylı verileri sunulmuştur. Ayrıca araştırılan kavramların bu çalışmalarda hangi anlamda ele alındığı bilgisine yer verilmiştir. En çok üretimin yapıldığı ve tarihi diğerlerine göre daha eskiye dayanan kentsel mekanda esneklik üzerine yapılan çalışmalarda "adaptasyon" kavramı önemli bir yere sahiptir. Ancak incelenen çalışmalar diğer anahtar kelimeleri de destekler şekilde adaptasyon kavramını daha çok iklim şartlarını adapte olmak olarak ele almıştır. Araştırmaya yapay zeka dahil edildikten sonra özellikle çalışmaların yapıldığı disiplinlerde önemli bir değişim gözlenmektedir: Mimarlık, kentsel planlama gibi alanlar daha geri planda kalmaktadır. Bunun yanında kentsel mekanlarda esnek kullanım ve yapay zeka üzerine yapılan çalışmalar oldukça azdır. Ancak uzun bir duraksama döneminden sonra özellikle yapay zekanın hayatlarımızda önemli yer kaplamaya başladığı yıllarda yayınların yapılmış olması bu alandaki potansiyelin göz ardı edilmemesi gerektiği izlenimini vermektedir.

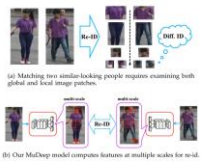
Avlularda esneklik araştırmalarının kentsel mekanda yapılan esneklik araştırmalarına göre oldukça az sayıda olmalarına karşın özellikle son yıllarda önemli bir artışın söz konusu olduğu görülmektedir. Ancak kent ve mimarlık disiplinlerinden çok yapı teknolojileri ve mühendislik alanlarında daha sık karşımıza çıkmaktadır. Bu durum avluların kentsel mekan bağlamından çok yapısal anlamda bir açıklık olarak ele alındığına işaret etmektedir. Nitekim incelenen çalışmalar da avluları iklime uyarlanabilirliği üzerinden ele almıştır. Araştırmanın bu adımına yapay zeka dahil edildiğinde de bu durum devam etmiştir.

Tablo 5. Bölüm 3'te yapılan bibliyometrik analiz sonuçlarını özetleyen tablo

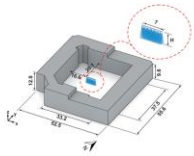
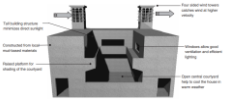
		Kategori yok			Kategori var		
		Anahtar Kelimeler	Önemli yıllar	Kategoriler	Anahtar Kelimeler	Önemli yıllar	Kategoriler
Kent	Kent + Esneklik	Adaptation City Cities Public space urban	Başlangıç: 1988 En çok: 2020 En düşük: 2003	- Urban Studies - Environmental Studies - Environmental Sciences - Architecture - Regional Urban Planning - Engineering Electrical Electronic - Computer Science Artificial Intelligence - Engineering Multidisciplinary - Nanoscience Nanotechnology - Phsics Applied - Construction Building Technology - Engineering Civil - Architecture - Energy Fuels - Green Sustainable Science Technology	City Public space Urban Cities Adaptation	Başlangıç: 2000 En çok: 2018 En düşük: 2000	- Urban Studies - Architecture - Regional Urban Planning
	Kent + Esneklik + Yapay zeka*	Virtual-reality Network Ambient intelligence Pedestrian recognition Sensor	Başlangıç: 2011 En çok: 2012 ve 2020 En düşük: 2014 – 2019, 2021, 2023				
Avlu	Avlu + Esneklik	Performance İmpact Design Hot Buildings	Başlangıç:1998 En çok: 2023 En düşük: 2001		Performance Adaptation Buildings Thermal comfort 2-sided wind catcher	Başlangıç: 2009 En çok: 2022 En düşük: 2011-2012, 2019	
	Avlu + Esneklik + Yapay zeka*	Courtyard climate change microclimate Support Vector Regression (SVR) machine learning	Başlangıç: 2021 En çok: 2021 ve 2024 En düşük:	- Mathematic - Robotic			

*Bu çalışmalarda disiplinlere göre filtreleme yapıldığında çalışma yer almadığından kategorileme yapılmamış çalışmalar ele alınmıştır.

Tablo 6. Kentsel/kamusal mekanlarda yapılmış en çok atıf alan çalışmalar

	Başlık	Kategori	Problem	Yöntem	Kavramlar	Görsel
Kent + esneklik	The city and the car (Sheller ve Urry, 2000)	- Geography - Public Administration - Urban Studies	Kent analizi çalışmalarında otomobillere yer verilmemesini eleştirmektedir.	Eleştiri ve kuramsal yaklaşım	Kent: Kent hem soyut hem somut (çoğunlukla toplumsal) anlamda ele alınmıştır. Esneklik: Otomobilin kentsel yaşama getirdiği esneklik ve sınırlılıklardan bahsedilmiştir.	
	The financialisation of rental housing: A comparative analysis of New York City and Berlin (Fields ve Uffer, 2016)	- Environmental Sciences - Ecology - Urban Studies	Konut satın alımının zorlaşması ve istikrarsızlığının kentsel mekanda soylulaşma ve terk edilme gibi etkileri	Analiz	Kent: Finansal işlemlerin gerçekleştiği ve etkilenen mekan. Esneklik: Daha çok stratejilerin uyarlanması anlamında kullanılmıştır.	
Kent + esneklik + yapaay zeka	Leader-Based Multi-Scale Attention Deep Architecture for Person Re-Identification (Qian ve ark., 2019)	- Computer Science, - Artificial Intelligence - Engineering, Electrical & Electronic	Kamusal bir alanda örtüşmeyen kamera görünümleri	Kişileri eşleştirmeyi amaçlayan "Kişi yeniden tanımlama" belirsiz farklılıkları tespit etmek amacıyla çok ölçekli derin öğrenme katmanı ve lider tabanlı dikkat öğrenme katmanından oluşan yeniden kimliklendirme ağı (MuDeep) önerilmektedir.	Kent: Kamera ile izlenebilen kentsel mekanlar. Esneklik: Modelin uyarlanabilmesi anlamında kullanılmıştır. Yapay Zeka: Kamera görüntülerinde kişi tanımlama için yöntem olarak kullanılmıştır.	
	Meeting People's Needs in a Fully Interoperable Domotic Environment (Miori ve ark., 2012)	- Chemistry, - Analytical - Engineering, Electrical & Electronic -Instruments & Instrumentation	Kullanıcıların alışkanlıklarını öğrenerek ve ihtiyaçlarını tahmin ederek yaşam kalitelerini artırmak.	Ortam Zekası tabanlı bir ortam gerçekleştirmeyi amaçlamaktadır. Daha üst ölçekte ev ya da kamusal alanda özel kullanıcı ihtiyaçları tahmin edilebilir olacağı düşünülmektedir.	Kent: kamusal mekanlar daha ileri çalışmalara önerilmiştir. Esneklik: cihazların birlikte çalışmaya uyarlanabilir olmasından bahsedilmiştir. Yapay Zeka: Ortam zekası oluşturmada yöntem olarak kullanılmıştır.	

Tablo 7. Avlu mekanlarında yapılmış en çok atıf alan çalışmalar

	Başlık	Kategori	Problem	Yöntem	Kavramlar	Görsel
Avlu+esneklik	Simulating the cooling effects of water spray systems in urban landscapes: A computational fluid dynamics study in Rotterdam, The Netherlands Montazeri, H. ve ark. 2017	- Ecology, - Environmental Studies, - Geography - Physical - Regional & Urban Planning, - Urban Studies	Isı artışının insan psikolojisi ve davranışı üzerindeki etkisini azaltmak için sürdürülebilir sistemler ihtiyacı.	Su püskürtme sistemlerinin soğutma potansiyelinin ölçülmesi için Hesaplamalı Akışkanlar Dinamiği simülasyonları kullanılmıştır.	Avlu: Araştırma alanı olarak kullanılmıştır. Esneklik: İklim değişimine uyarlanabilirlik, sürdürülebilirlik	
	A numerical investigation into the feasibility of integrating green building technologies into row houses in the Middle East Calautit, J.K. ve ark. 2013	Architecture	Geleneksel rüzgar kulelerinin geliştirilerek ekonomik yarar sağlaması.	Mevcut sıra konut modellerine uyarlanabilen rüzgar kulesi sistemi geliştirilmiştir.	Avlu: Geleneksel evlerin avluları konu edinilmiştir. Esneklik: İklim değişimine uyarlanabilirlik ve sıra konutların avlularına uyabilecek tasarımın yapılması olarak ele alınmıştır.	
Avlu+esneklik+yapay zeka	Applied Machine Learning Algorithms for Courtyards Thermal Patterns Accurate Prediction Diz-Mellado, E. ve ark., 2021	Matematik	Bina performansını ölçen makine öğrenimini geliştirerek yapı dışındaki karmaşık termodinamikleri olan avluların sıcaklığı ölçebilmek.	Makine öğrenimi modellerinden Destek Vektör Regresyon (Support Vector Regression - SVR) yöntemi	Avlu: sıcaklığı ölçülebilir yarı açık mekan olarak ele alınmıştır. Esneklik: iklime uyarlanabilirlik olarak ele alınmıştır. Yapay Zeka: Makine öğrenimi modelleri yöntem olarak kullanılmıştır.	
	ASC: Adaptive Skill Coordination for Robotic Mobile Manipulation Yokoyama, N. ve ark., 2023	Robotik	Bir robotun toplama, taşıma gibi eylemleri gerçekleştirmek için eğitiminde karşılaşan zorluklar.	Uyarlanabilir Beceri Koordinasyonu ile pekiştirmeli öğrenme simülasyon alanlarda gerçekleştirilir.	Avlu: Eğitimin yapıldığı simüle edilmiş iç mekanlardan biridir. Esneklik: Sistemin başka araçlara uyarlanabilir olması olarak ele alınmıştır. Yapay Zeka: Pekiştirmeli öğrenme olarak yöntemde kullanılmıştır.	

5. Sonuç

Araştırma kapsamında literatürdeki çalışmalar hakkında genel olarak aşağıdaki sonuçlara varılmıştır:

- Neredeyse tüm taramalarda iklimsel kriz, sıcaklık değişimi, termal konfor, yapısal performans gibi kavramlar ön plana çıkmıştır. Bu durum küresel bir sorun olan iklim krizi, küresel ısınmanın akademik araştırmalarda önemli bir karşılığı olduğunu göstermektedir.
- Kentsel mekanın soyut olarak ele alınmadığı çalışmalarda daha çok sokakların araştırma alanı olduğu görülmektedir.

- Avluyu inceleyen çalışmalarda avluların kentsel avludan ziyade geleneksel yapı içindeki avlular olarak ele alındığı görülmektedir.
- Avluların daha çok sıcaklık değişimi ve termal konfor analizine yönelik çalışmalar yer almaktadır.
- Yapay zeka incelenen tüm çalışmalarda yöntem olarak kullanılmıştır.

Tüm bu sonuçlar çalışmanın amacı ve geleceği yönünden incelendiğinde ise aşağıdaki sonuçlar ortaya çıkmaktadır:
- Literatürde kentsel ölçekte ve kamusal olarak ele alınan avlu tartışmaları eksik görünmektedir.
- Esneklik bağlamında güncel olan sürdürülebilirlik alanının öne geçmesi olağan bir sonuçtur ancak kentsel mekanın esnek, birden çok ihtiyaca cevap veren tasarımlarına yeterince odaklanılmamıştır.
- Yapay zekanın gittikçe genişleyen kullanım alanı kentsel mekanda yapılacak araştırmalarda sıcaklık ölçümü veya alan tespitinin ötesine geçme potansiyelleri taşımaktadır.

Elde edilen sonuçlar arasında çalışmanın ana konusu olan avluların esnek kullanım potansiyellerine odaklanıldığında, ön plana çıkan anahtar kelimeler arasında tasarım ve uyarlanabilirlik gibi araştırmanın odaklandığı konuya yönelik kelimeler görülse de incelenen yayınlarda kelime anlamlarının daha çok sıcaklık değişimi, termal konfor sağlama arayışı ile ilgili olduğu ortaya çıkmıştır. Avluların kent ölçeğindeki yeri ve öneminin yeterli seviyede ele alınmadığı görülmektedir: İklim, sıcaklık avantajlarıyla ön plana çıkarılan avluların psikolojik, dıştan soyutlanma, arayüz mekanı olma, genel ve özel mekan arasında olmasının getirdiği sosyal zenginlikleri gibi mekânsal özelliklerinin geri planda kalmıştır. Özellikle de yapay zekanın tasarımda kullanılan potansiyellerinin avlu özelinde değerlendirilmediği görülmektedir.

Özetle, avluların esnek kullanım potansiyeli literatürde iklim değişikliğine uyarlanabilirlik tartışmasının ötesine çok fazla geçememiş, incelenen çalışmalarda avlular çoğunlukla kentsel bağlamdan, gündelik yaşamdan ve olası acil durumlardan kopuk bir şekilde yer almaktadır. Oysa ki zengin mekânsal özellikleriyle avluların tarihte de birden çok işlev ile kullanımının örnekleri görülmekte ve günümüzde kent dokusunda nefes alan önemli açıklıklar oldukları bilinmektedir. Çok aşamalı literatür taraması ve analizinde elde edilen bu sonuçları ile çalışma, literatürde eksik olduğunu kanıtladığı; gündelik yaşamda, birbirinden farklı kentsel etkinliklerde ya da olağanüstü hallerde (afetler, sosyal etkinlikler gibi) kentsel avluların esnek kullanım potansiyellerini değerlendirebilecek araştırmalar için temel oluşturmaktadır.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	C.F.	H.A.
K	50	50
T	50	50
Y	50	50
VTI	50	50
VAY	50	50
KT	50	50
YZ	50	50
KI	50	50
GR	50	50
PY	50	50
FA	50	50

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

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Research Article
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IN SILICO PREDICTION OF EGFR INHIBITORS FROM THIOPHENE DERIVATIVES

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Abstract: Cancer is one of the biggest global health problems and is the second leading cause of death worldwide. Cancer also causes great damage to economy. Unfortunately, there is still no effective treatment method against this disease today, and the mortality rates in certain types are still very high. Medical research can now be done faster and safer with the aid of in silico studies. These studies save time for researchers and accelerate new drug discoveries. In our study, thiophene derivatives with important efficacy in cancer treatment were focused on and the affinity of the small molecule structures determined as candidates to the Epidermal Growth Factor Receptor (EGFR), known to be the key receptor in cancer, was examined. First, molecular docking studies were performed, and then long-term molecular dynamics (MD) simulations were carried out. Finally, anti-cancer activity predictions based on Quantitative Structure-Activity Relationship (QSAR) were performed. Co-crystallized ligand Erlotinib, taken from the Protein Data Bank (PDB), was used as a positive control and compared with candidate drugs using the same procedures. In light of the analysis of virtual screening, MD, MM/GBSA, and QSAR predictions, the top three molecules and their MM/GBSA scores were identified as follows: OSI 930 (-65.81 kcal/mol), Neltenexine (-49.53 kcal/mol), and Tenonitrozole (-41.95 kcal/mol). As a result, in this study, candidate molecules that inhibit EGFR and have the highest potential as anti-cancer drugs among thiophene-derived compounds were determined and detailed in silico analyzes were performed. This study holds importance as it may guide future anti-cancer drug discovery studies.

Keywords: EGFR, MD simulation, Molecular docking, Small molecules, Thiophene derivatives.

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1. Introduction

With the increasing number of cases, cancer is the second disease that causes the most deaths after cardiovascular diseases, and it is likely to come first in terms of both death and health expenditures in the coming years (Collaboration, 2019). In a developing country like Türkiye, currently, researchers are working hard on the treatment of this disease with low budget, and the number of articles on local cancer problems is increasing rapidly every year (Pramesh et al., 2022) . Considering the research budgets used and the number of researchers working, the process progresses very slowly with classical drug development methods. At the same time, it is very costly to pass a candidate drug molecule to phase stages. Discovery of a drug to prevent a disease is approximately $2-3 billion and takes 10 to 15 years but it is $300 million and 6.5 years for repurposing drugs (Weth et al., 2024). Moreover, there is no guarantee that a commercial product will be obtained as a result of these expenses. While normally only a few candidate drugs tested can be approved at the end of the process, this success rate can reach higher for drugs discovered in silico. Today, there is an urgent need to use computer-based drug discovery methods to overcome these limitations. Thanks to computer-based drug discovery, more effective, more target-specific and safer drug candidates can be found in a short time (Berdigaliyev and Aljofan, 2020).

In silico drug discovery process is a set of computer-based computational approaches, including high-throughput virtual screening, molecular docking, molecular dynamics simulations and artificial intelligence-based machine learning methods. In silico methods, which save on human resources, space and time, are increasing their effectiveness and usability day by day. With the aid of these methods, drug candidate molecules in the pool are evaluated for minimum toxicity (Stillman et al., 2020; Shaker et al., 2021).

It enables us to complete the processes including pre-clinical trials in a very short time, and to discover the best drug by enabling the selection of the most effective and target-specific candidate molecules (Gagic et al., 2020). For this purpose, drugs can be designed from scratch or screened from various databases containing many small drug molecules. Studies of repositioning existing, known, and also approved drugs against a different disease, such as the FDA-approved drug library, constitute the principle of drug repurposing studies. Drug repositioning studies appear to be the safest method because they enable the use of existing drugs with known side effects and pharmacodynamic potential

(Masuda et al., 2020; Turanli et al., 2021). At the same time, the first method used for emergency use in epidemic diseases such as COVID19 and extraordinary situations is again drug repurposing studies (Durdağı, 2020).

Thiophene derivatives are key structures consisting of a heterocyclic skeleton containing a ring of sulfur and four carbon atoms (Gramec et al., 2014). The higher number of the anticancer drugs used in clinics have a heterocyclic structure (Nehra et al., 2022). In this respect, many studies have shown that Thiophene derivatives, which are known to be a priority for drug discovery, have high anti-cancer potential. In addition, thiophenes are more reactive than their counterparts thanks to the sulfur atom in their structure. At the same time, they are more polar and exhibit a more biocompatible character thanks to their high solubility in water. The number of trials of thiophene derivatives, which stand out with these properties, in anti-cancer studies in the literature is increasing day by day, and they have high potential to become candidate drug molecules (Vallan et al., 2021; Kuchana et al., 2022).

There are known important protein targets in cancer such as BCL2 (Zhang et al., 2021), MCL2 (Harmanen et al., 2023), PI3K (Jones et al., 2022), PTEN (Turnham et al., 2020) and EGFR (Sun et al., 2021). Epidermal growth factor receptor (EGFR), which is involved in many pathways in the cell, such as cell signaling pathways that control cell division and survival, ensures homeostasis (Uribe et al., 2021). In recent years, research has focused on receptors expressed in cancerous cells, thus targeting drugs to a specific cell type has become possible. Personalized treatment has made significant progress, especially in diseases that can rapidly develop resistance to drugs, such as cancer. EGFR is one of the most targeted receptors and many researchers see it as a key target in the treatment of cancer (da Silva Santos et al., 2021; Tian et al., 2022). Within silico studies, various target molecules can be quickly tested against a receptor expressed in a known type of cancer (Sibuh et al., 2021). In this research, 10 different Thiophene derivatives were identified to be used in the treatment of cancer, which is a major global public health problem. Then, these thiophene derivatives were subjected to docking studies for the EGFR protein. Molecular Mechanics/Generalized Born Surface Area (MM/GBSA) analysis was performed for the 5 derivatives with the best scores, and the results were evaluated by comparing them with the reference molecule.

2. Material and Methods

2.1. Preparation of the Thiophene-containing Compounds for Docking

In this study, ten compounds containing thiophene were obtained from the literature. Ligands were prepared using the LigPrep module of Schrödinger's Maestro molecular modeling package (Madhavi Sastry et al., 2013; Jamal et al., 2015). The physiological environment and ionization states of all ligands were adjusted at physiological pH 7.4 using Epik (Shelley et al., 2007).

2.2. Protein Preparation and Grid Box Generation

In this study, the tyrosine kinase domain of the Epidermal Growth Factor Receptor (EGFR) was utilized in a co-crystallized form with the 4-anilinoquinazoline inhibitor, erlotinib. The structure corresponding to this complex is identified by the Protein Data Bank (PDB) accession code 1M17. The Prime Module of the Schrödinger Molecular Modeling Package was used to complete structure with missing side chains and loops. Disulfide bonds were formed. Protonation states were set at a physiological pH of 7.4 using PROPKA (Bas et al., 2008). After the preparation of the ligand and protein, the grid box was created in the active region by taking the coordinates of the protein's co-crystallized ligand in the PDB as the center. For docking studies, the Glide docking program of the Maestro molecular modeling package was used with standard precision (SP) settings (Siyah et al., 2023). The conformation and the score of the docking poses obtained with the X-ray data of the co-crystallized structures were compared.

2.3. Molecular Dynamics Simulations

Atomic-level MD simulations contribute to the understanding of biological systems. In this study, classical MD simulations were applied for potentially effective compounds against the EF2K target. Through the Desmond MD simulation program, the compounds identified in the docking simulations along with the apo form of the target protein were added to the simulation (Bowers et al., 2006). The systems were surrounded with an orthorhombic box containing TIP3P water molecules, and interactions at the atomic level were determined using the OPLS3e force field (Roos et al., 2019). The systems were simulated with NPT assembly at 310K temperature and 1 bar pressure. The Nose-Hoover thermostat and the Martyna-Tobias-Klein barostat were used to keep temperature and pressure constant (Evans and Holian, 1985; Martyna et al., 1994). The systems were minimized and balanced with Desmond's default protocols, and MD simulation was performed for each system for 100 ns, 100 frames were recorded.

2.4. MM/GBSA Calculations

Interactions such as hydrogen bonds, hydrophobic interactions, ion pairs and water bridges established between the ligand and the active site are vital for the integration of small molecules into the catalytic part of the protein. The free energy values between protein and ligand of the molecules obtained from Maestro were calculated with the MM/GBSA methodology used in the Prime module of Schrödinger's molecular modeling package. Prime simulates these interactions in detail using the VSGB 2.0 resolution model (Jacobson et al., 2004).

2.5. ADME Analysis and Anticancer Activity Prediction with Binary QSAR Models

All molecules that underwent docking and 100ns MD were subjected to Metacore Metadrug analyzes from Clarivatives Analytics. Absorption, Distribution, Metabolism, and Excretion (ADME) properties were calculated. Therapeutic activity predictions for cancer were made with machine learning based binary QSAR models. The sensitivity, specificity, accuracy and model quality and accuracy of the models were validated with Matthews Correlation Coefficient (MCC). The cut off value was accepted as 0.5 (Ekins et al., 2006).

3. Results and Discussion

In this study, thiophene derivatives that we obtained from the literature and the reference molecule were docked to the EGFR target. Docking scores are the important metric that determines how strong a binding affinity a molecule can display with a target protein. Scores are expressed in negative energy units, with lower (more negative) scores meaning stronger binding affinity (Muegge and Rarey, 2001). In the light of the results of the docking study scores performed with the Glide module of the Maestro program, it was discovered that the Erlotinib molecule, which is stated as the reference molecule for EGFR and is co-crystallized in the PDB, binds to EGFR most strongly. The determination that it binds with the strongest score and it also binds through known interaction amino acids confirmed the accurate and reliable calculation results of the program we used (Türkmenoğlu, 2022).

The docking score of the reference molecule (Erlotinib), which is currently used as an anticancer drug (Zhou et al., 2011) and was included in our study as a positive control, was calculated as -8.21 (Figure 1). In the experimental group, the ligand that followed the reference drug with the closest score was the OSI930 molecule with -6.142 (Figure 2). This is followed by Tenosal with -6.06 kcal/mol and Neltenexine ligands with -6.04 kcal/mol. Suprofen molecule has average docking scores of -5.48, Cliprofen molecule -5.40, and Tenonitrozole molecule -5.27. The weakest binding ligands were VX-759, Midestein, VCH-916 and Taurostein, with docking scores of -4.994, -4.865, -4.442 and -4.340 kcal/mol, respectively. In this study, the cut off value was determined as -5.00 kcal/mol. While weaker binding ligands were eliminated, ligands with a stronger binding (more negative) score than -5.00 kcal/mol were selected for more detailed studies (Table 1).

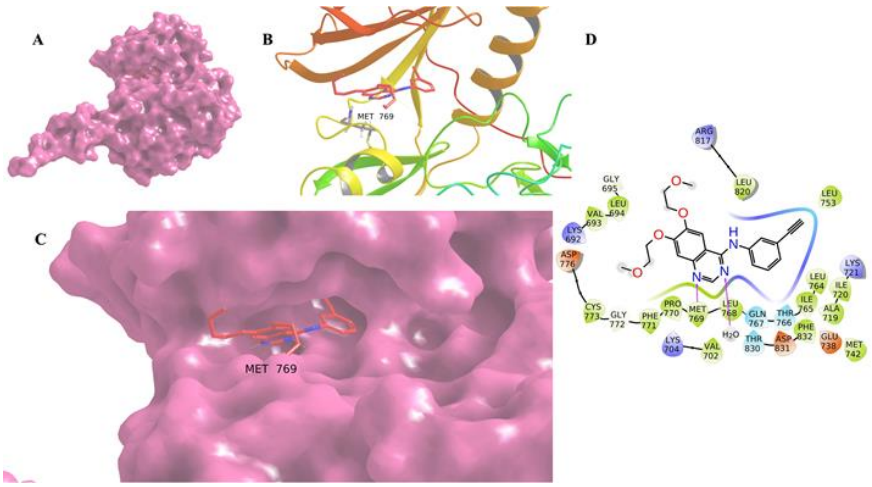

Figure 1. A) The best docking conformation of the Erlotinib ligand in the binding pocket of EGFR protein, B) Erlotinib-EGFR interaction in ribbons representation, C) Amino-acid contact of EGFR in EGFR- Erlotinib receptor-ligand interaction, D) 2D visualization of the interactions between EGFR and Erlotinib ligand.

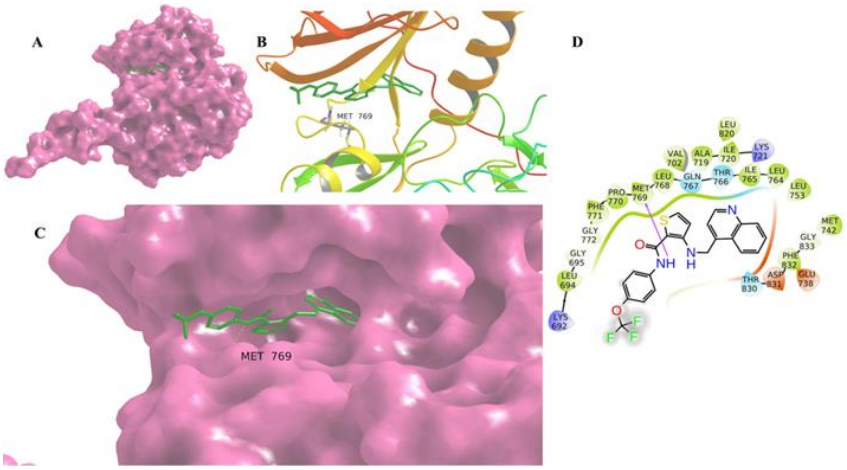

Figure 2. A) The best docking conformation of the OSI930 ligand in the binding pocket of EGFR protein, B) OSI930-EGFR interaction in ribbons representation, C) Amino-acid contact of EGFR in EGFR-OSI930 receptor-ligand interaction, D) 2D visualization of the interactions between EGFR and OSI930 ligand.

The complexes belonging to the best docking poses of the selected molecules were subjected to 100ns MD simulations to observe long-term protein-ligand interactions for detailed analyses (Agarwal et al., 2022). During the simulation, 100 frames were obtained, and the binding free energies of these frames were calculated with Molecular Mechanics/Generalized Born Surface Area (MM/GBSA) analysis. MD-MM/GBSA analysis, an advanced method that uses molecular mechanics, is based on the calculation of the binding free energy change of the complex formed by small molecule drug candidates with the target biological macromolecule. This method evaluates the interactions of compounds with the target protein from a more detailed and dynamic perspective after molecular dynamics (MD) simulations. MM/GBSA analyzes were performed with the Prime module of the Maestro Molecular Modeling program (Palanivel et al., 2022).

Table 1. Docking (kcal/mol) and MM/GBSA (kcal/mol) scores of thiophene derivatives. Molecules are ranked from strongest MM/GBSA score to weakest

Complex	Docking (kcal/mol)	100 ns MD – MM/GBSA (kcal/mol)
OSI930	-6.14	-65.81
Erlotinib (REF)	-8.21	-64.72
Neltenexine	-6.04	-49.53
Tenonitrozole	-5.27	-41.95
Suprofen	-5.48	-34.79
Cliprofen	-5.40	-29.39
Tenosal	-6.06	-25.12

According to MM/GBSA scores, the binding free energy of Erlotinib is -64.72 kcal/mol. Remarkably, OSI930 emerged as the best candidate compound with a binding free energy of -65.81 kcal/mol, even outperforming the reference molecule.

Neltenexine was the second-best drug candidate compound with a binding free energy of -49.53 kcal/mol MM/GBSA. Tenonitrozole was also one of the compounds that showed strong binding and high stability with -41.95 kcal/mol. Suprofen, Cliprofen and Tenosal MM/GBSA scores were determined as -34.79, -29.39 and -25.12 kcal/mol, respectively (Table 1). In the MM/GBSA analysis, the cut-off value was determined as -40.00 kcal/mol and compounds with better binding affinity were examined in further studies as potential EFGR inhibitor drug candidates.

The amino acids with which the reference drug Erlotinib interacts for 100 nanosecond (ns) and the type of these interactions were analyzed in detail. As the most important interaction, it was observed that Erlotinib continuously interacted with Met769 throughout the entire simulation period, thanks to H bonds. Leu694, Ala719, Leu820 were included as significant hydrophobic interactions. It formed salt bridges with Thr766, Cys773, Asp776 and Thr830. In the light of our results, it was determined that Leu694, Ala719, Thr766, Cys773, Asp776, Leu820, Leu830 residues, especially Met769, were the crucial amino acids that ensure the Erlotinib-EGFR interaction (Figure 3 and 4).

After determining the amino acids and bond structures that are important in EGFR binding via erlotinib, drug candidate target molecules were also subjected to the same analysis and how the proposed drug candidates interact with the EGFR receptor, with which bond type, over which amino acids and for how long they interact with this receptor, they were examined. It was determined that the compound OSI930, which had the best docking and MM/GBSA binding scores among the candidate compounds, interacted with Met769, the most important amino acid for EGFR interaction, similar to the known EGFR inhibitor Erlotinib. The crucial amino acids that provide OSI930-EGFR interaction were determined to be Leu694, Val702, Ala719, Lys721, Met769, Leu820. While it formed hydrogen bonds with Met769, its interactions with other amino acids were highly hydrophobic interactions. These hydrophobic interactions were also observed in the study of Chunaifah et al. (2024).

In addition, in our study, salt bridges with Cys773, Asp776 and Thr830 were also observed, similar to the reference drug, although not as strong as that of the reference drug used. The amino acids with which the prominent interactions occurred in our study are common with the key amino acids determined for Erlotinib and candidate drugs as a result of docking and simulation in the study of Eldehna et al (2022) (Eldehna et al., 2022). Saini et al. (2022) (Saini et al., 2022) also stated that EGFR interacts with Erlotinib via hydrogen bonding via Met769, which has a bond distance of 2.70 Å, and noted the importance of hydrophobic interactions with amino acids Leu694, Ala719, Lys721, Leu764 and Leu820. Studies by Yang et al. (2020) (Yang et al., 2020) have also indicated that Met769 has a key role in EGFR binding.

It is an important point that the binding patterns of different compounds may be slightly different from each other, which is responsible for the activity variations, but in general, inhibitors such as Erlotinib form a hydrogen bond with the NH backbone of Met769, especially in the hinge region. Moreover, often these compounds are deeply embedded in the EGFR through conserved hydrophobic interactions (Nasab et al., 2018). Our results support that the best compound, OSI930, which we claim has the potential to be an anti-cancer drug, is observed to be embedded in the EGFR, similar to Erlotinib, by forming a hydrogen bond with the NH backbone of Met769 in the hinge region and thanks to the hydrophobic interactions it carries out.

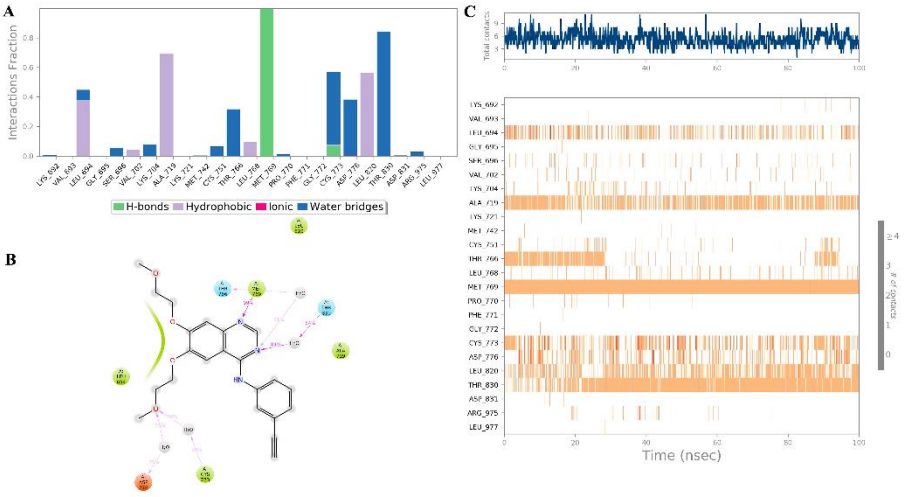

Figure 3. A) The type of interactions that occur between the Erlotinib ligand and the EGFR target during the MD simulation. B) 2D interaction analysis of the Erlotinib in the binding pocket of the protein. C) Time-dependent analysis of the Erlotinib-EGFR contact residues throughout 100 ns simulation.

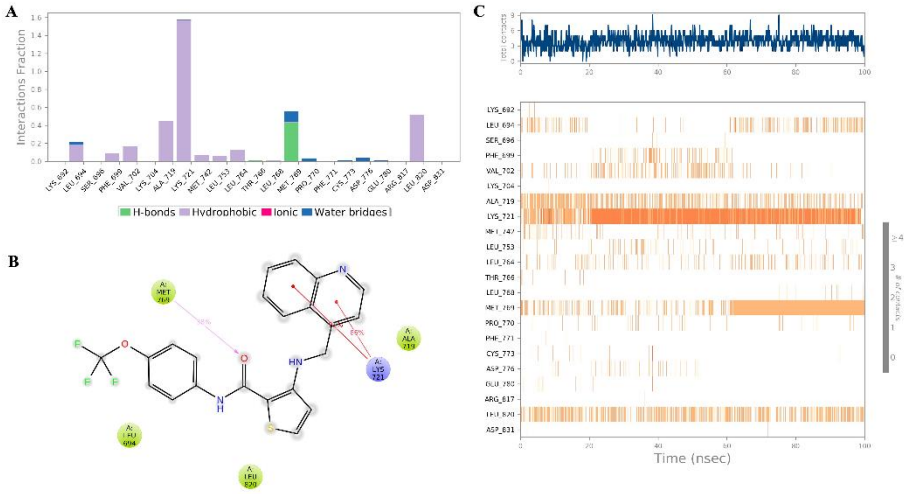

Figure 4. A) The type of interactions that occur between the OSI930 ligand and the EGFR target during the MD simulation. B) 2D interaction analysis of the OSI930 in the binding pocket of the protein. C) Time-dependent analysis of the OSI930-EGFR contact residues throughout 100 ns simulation.

After these studies, the ADME and anti-cancer properties of the reference molecule and selected drug candidate molecules were predicted in Clarivate analytics' MetaCore/MetaDrug platform for more detailed analysis (Celik et al., 2022). For this purpose, machine learning-based ADME and cancer therapeutic dual Quantitative structure–activity relationship (QSAR) models were used. Therapeutic activity values obtained from MetaCore Clarivate estimate the potential anti-cancer effects of the compounds. If the scores of compounds are higher than 0.5, it means that those compounds are predicted to show strong therapeutic potential and efficacy. Cancer therapeutic activity QSAR model predicted Erlotinib as a drug candidate that may have highly anti-cancer effects. This confirmed the accuracy and reliability of our studies and forecasting method. When the results are examined, the QSAR models we used expect Tenonitrozole to have a very high anti-cancer effect, and similarly, OSI930 and Neltenexine compounds were predicted by machine learning-based method to be good drug candidates in cancer. Cliprofen, Suprofen and Tenosal compounds, which were at the bottom of the MM/GBSA analysis, were found to be weak in terms of anti-cancer activity at this step (Table 2).

The novel small-molecule OSI-930 is a multi-kinase inhibitor which effectively targets vascular endothelial growth factor receptor 2 (VEGFR2)/kinase splicing domain receptor (KDR), platelet-derived growth factor receptor (PDGFR) and c-Kit (Garton et al., 2006). First-in-human phase I study was conducted to evaluate safety, maximum-tolerated dose (MTD), pharmacokinetics, pharmacodynamics, and antitumor activity of OSI-930 in

patients with advanced solid tumors and it was found that OSI-930 is well tolerated with clinically significant antitumor effects (Yap et al., 2013). However, there is no previous study showing that it may exert its effect by binding to the EGFR target. Although our study supports the literature and phase 1 studies, it is important in terms of showing the target it binds to, simulation of the interactions that occur, the type and duration of the interactions, and also the detection of important amino acids involved in the interaction.

It has been suggested that the co-inhibition of VEGF and EGFR, which are two key targets in cancers that have independent but highly interdependent interactions with each other, is important in cancer treatment and overcoming resistance to cancer (Tabernero, 2007). Macpherson et al. (2013) (Macpherson et al., 2013) study shows that the combined use of OSI-930 and erlotinib, a selective EGFR kinase inhibitor, has a synergistic effect. While finding the maximum tolerated dose of OSI-930 that could be combined with erlotinib. Discovering that OSI-930, which is primarily a VEGF inhibitor, also inhibits the EGFR protein underscores a crucial result for cancer therapy. In conclusion, our study emphasizes the importance of OSI-930 as a dual inhibitor that can target both EGFR and VEGF pathways and reveals its potential as a promising therapeutic option for cancer treatment (Falchook and Kurzrock, 2015; Wang et al., 2023).

Neltenexine, an elastase inhibitor, is a mucolytic agent that may be effective against pulmonary disease (Cattaneo, 2001). However, literature information about Neltenexine is limited. In-depth biochemical analyses are needed (Braga et al., 1995). Moreover, to date, no docking simulation studies have been conducted on Neltenexine. Therefore, its potential effects and mechanism of action need to be investigated in more detail. Our research provides an innovative perspective in that the Neltenexine molecule is docked for the first time and proposed as a repurposed EGFR inhibitor for the first time in this study.

Tenonitrozole, an antiprotozoal therapeutic agent approved by European regulatory authorities, prescribed primarily against urogenital trichomoniasis (Lynch et al., 2019; Guo et al., 2023). Tenonitrozole has not been previously investigated in cancer research. Our study pioneers the investigation to uncover its potential as an anti-cancer drug candidate by highlighting its EGFR inhibitory activity.

Table 2. Prediction of cancer therapeutic activities of selected candidate drug molecules. Tanimato prioritization (TP) values are given in parentheses, indicating the similarity of the analyzed structure to the most similar compound in the training set.

Name	MW	Rule Of 5	RBN	HBA	HBD	Reactive	Cancer (TP)
Reference Drug (Erlotinib)	393.443	OK	11	5	1	OK	0.86 (100.00)
Tenonitrozole	255.27	OK	4	4	1	R	0.83 (34.05)
OSI930	443.44	OK	8	4	2	OK	0.79 (100.00)
Neltenexine	489.25	OK	6	3	4	R	0.65 (52.11)
Cliprofen	293.74	OK	4	3	0	OK	0.29 (46.34)
Suprofen	259.3	OK	4	3	0	OK	0.28 (40.97)
Tenosal	247.24	OK	4	4	0	OK	0.17 (41.95)

1 Formula Molecular formula.
2 HBA Number of hydrogen bond acceptors.
3 HBD Number of hydrogen bond donors.
4 MW Molecular weight.
5 RBN Number of rotatable bonds.
6 Reactive Identify reactive groups in molecules. OK means that the metabolite does not contain spontaneously reactive groups, R means it does. MetaDrug currently includes 89 rules to predict likely reactive metabolites such as quinones, aromatic and hydroxyl amines, acyl glucuronides, acyl halides, nepoxides, thiophene-S-oxides, furans, phenoxyl radicals, phenols, and aniline radicals.
7 RuleOf5 Lipinski rule of five can be used to indicate whether a molecule is likely to be orally bioavailable. A molecule should not have more than 5 hydrogen bond donors, not more than 10 hydrogen bond acceptors, a molecular weight under 500, and a partition coefficient log P under 5. Rule of five-compliant molecules are marked as OK, non-compliant as Poor. Reference: Lipinski, et al., 2001 (PMID: 11259830).
8 Cancer Potential activity against cancer. Cutoff is 0.5. Values higher than 0.5 indicate potentially active compounds. Training set consists of approved drugs. Model description: Training set N=886, Test set N=167, Sensitivity= 0.89, Specificity=0.83, Accuracy=0.86, MCC=0.72. Reference: Clarivate Analytics.

4. Conclusion

In recent years, computer-based cancer candidate drug development research has gained momentum. In this study, molecules with the "thiophene scaffold", which is claimed to have a key role in cancer, were scanned from the literature and docked against the EGFR target, whose inhibition is known to be necessary in cancer in many publications. The duration, type and stability of the interactions between the drug candidates and the target protein, which were found to bind strongly with high affinity according to the docking score, and the important amino acid residues that play a role in these interactions were examined in detail with long-term MD simulations and mmgbsa analyses. Adme properties and anticancer activity of selected drugs were predicted with Machine Learning-based binary QSAR Models. In the light of the results, three candidate molecules were found to be

EGFR inhibitor drugs: OSI930, Tenonitrozole and Neltenexine. Upon evaluating MMGBSA calculations, concerning both binding free energy and binding stability, OSI930 emerges as the best candidate among these candidate molecules. Our research highlights the high potential of OSI930 as a dual inhibitor effectively targeting both EGFR and VEGF pathways, providing a promising strategy for cancer treatment. Furthermore, we expand the scope of potential therapeutics in cancer treatment by introducing Tenonitrozole and Neltenexine as novel EGFR inhibitor candidates. This research holds significance in providing novel inhibitor candidates against EGFR and providing guiding future studies. Future research should focus on performing extensive in vitro and in vivo experiments to validate the effectiveness and safety of these candidate molecules.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	P.S.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflicts of interest

The author declare that there are no conflicts of interest regarding the publication of this research.

Ethical approval

No ethical approval was required for this research as no studies were conducted involving animals or humans

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YENİ KARARSIZ BULANIK PORTFÖY OPTİMİZASYONU MODELİ VE TÜRKİYE UYGULAMASI

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Özet: Geleneksel portföy teorisi bir dizi hisse senedi ve diğer finansal varlıkların getiri ve riskler gibi niceliksel verilere bağlı olarak optimum yatırım oranlarının bulunması üzerine tasarlanmıştır. Ancak getiri ve risk arasındaki ilişki önemli bir kuram olup getirisini yükseltmek isteyen yatırımcı büyük risk oranlarına katlanmak zorunda kalabilir. Bu veriler her zaman net olarak bilinmeyebilir ve belirsizliğe sebep olurlar. Bu durumda kesin verilerle çalışmak yerine bulanık teorinin yardımıyla oluşturulan yeni modellerin gelişmesine ihtiyaç duyulmuştur. Bu çalışmada bulanık teorinin genişletilmiş bir uzantısı olan kararsız bulanık teori ele alınmış ve portföy optimizasyonu için yeni bir karasız bulanık matematiksel model geliştirilmiştir. Model bulanık riskin enküçüklenmesi halinde bulanık getirinin en büyük değerinin bulunması üzerine kurulmuştur. Bu model Türkiye'de Borsa İstanbul 50 (BIST 50)'da yer alan hisse senetlerinin günlük kapanış değerleri alınarak portföy seçeneklerinin belirlenmesi amacıyla kullanılmış ve yorumlanmıştır.

Anahtar kelimeler: Portföy optimizasyonu, Kararsız bulanık teori, Karasız bulanık matematiksel programlama

New Hesitant Fuzzy Portfolio Optimization Model and Application in Türkiye

Abstract: Traditional portfolio theory is designed to find optimum investment rates for a set of stocks and other financial assets based on quantitative data such as returns and risks. However, the relationship between return and risk is an important theory and investors who want to increase their returns may have to bear large risk rates. These data may not always be known clearly and cause uncertainty. In this case, instead of working with exact data, there was a need to develop new models created with the help of fuzzy theory. In this study, hesitant fuzzy theory, which is an extended extension of fuzzy theory, is discussed and a new unsteady fuzzy mathematical model is developed for portfolio optimization. The model is based on finding the maximum value of fuzzy return if the fuzzy risk is minimized. This model was used and interpreted to determine portfolio options by taking the daily closing values of the stocks listed in Borsa Istanbul 50 (BIST 50) in Türkiye.

Keywords: Portfolio optimization, Hesitant fuzzy theory, Hesitant fuzzy mathematical programming

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1. Giriş

Portföy optimizasyonu, yatırımcının risk ve getiri hedeflerine en uygun şekilde yatırım yapmasını sağlayan bir süreçtir. Temel amacı, en uygun risk seviyesinde en büyük getiriyi elde etmek veya kendilerine en uygun getiri değeri için risk seviyesini enküçüklemektir. Portföy optimizasyonunda yaygın olarak kullanılan araçlardan biri, Markowitz'in Modern Portföy Teorisi'dir (Markowitz, 1952). Bu teori, bir portföyün riskini enküçüklerken getirisini enbüyüklemeyi amaçlar ve varlıkların risk-getiri profillerini dikkate alarak en iyi portföy kombinasyonunu bulmayı hedefler. Teori risk ölçüsünü ortalama varyans yöntemi ile ifade etmektedir. Markowitz diğer bir çalışmasında varyans yerine yarı varyansı risk ölçüsü olarak kullanmayı önermiştir (Markowitz, 1959). Markowitz'in teorisine dayanarak literatürde çok çalışma yürütülmüştür, bunlardan bazıları, Sharpe (1964), Lintner (1965) ve Mossin (1966) olarak sıralanabilir. Konno ve Yamazaki (1991), risk ölçümü olarak ortalama mutlak sapmayı önermiştir. Kerstens ve ark. (2011) ile Kim ve ark. (2014) risk ölçüsü olarak çarpıklık ve basıklık katsayılarını kullanmışlardır.

Zadeh (1965) belirsizliği tanımlamak amacıyla bulanık teorinin temellerini atmıştır. Bu teorinin temel ilkeleri kullanılarak bulanık teori genişletilerek sezgisel bulanık küme kavramı Atanassov (1986) tarafından geliştirilmiştir. Torra (2010) kararsız bulanık kümeler teorisini ortaya atmıştır. Dual kararsız bulanık kümeler Zhu ve ark. (2012) tarafından kurgulanmıştır. Kararsız bulanık dilsel terim kavramı Rodríguez ve ark. (2012) tarafından geliştirilmiştir. Chen ve ark. (2013a) aralık değerli karasız bulanık kümeler, Hao ve ark. (2017) olasılıklı dual kararsız bulanık kümeler, Zeng ve ark. (2021) ise ağırlıklı hiyerarşi kararsız bulanık kümeler konularında çalışmışlardır.

Literatürde belirsiz parametrelere sahip portföy optimizasyon problemini araştıran birçok makale bulanmaktadır. Örneğin, Watada (1997), bulanık portföy seçimi problemini ele alarak beklenen getiri ve riskteki belirsizleri incelemiştir. Parra ve ark. (2001) üç kriterli

(getiri, risk ve likidite) bir portföy seçimi modeli önermiş ve modeli bulanık hedef programlama yaklaşımı kullanarak çözmüşlerdir. Lin ve ark. (2005) yöneticilerin iş portföylerinin genel rekabet gücünü daha iyi anlamalarına yardımcı olmak için bulanık küme teorisini dahil ederek, portföy matrisleriyle birlikte sistematik bir yaklaşım önermişlerdir. Fang ve ark. (2006) bulanık karar teorisine dayalı üç kriterli (getiri, risk ve likidite) bir portföy yeniden dengeleme modeli sunmuşlardır.

Ammar (2007) bulanık portföy optimizasyon problemini dışbükey karesel programlama problemi olarak modelleyerek, kabul edilebilir bir çözüm sağlamıştır. Huang (2011), getirilerin belirsiz olduğu durumda, bir risk eğrisi sunmuş ve buna bağlı olarak ortalama risk modeli geliştirmiştir. Huang ve Qiao (2012), getirilerin karar vericilerin bilgileri temel alınarak bulanık değişkenler olarak tanımlandığı bulanık ortamlarda çok dönemli portföy seçimini araştırmışlardır. Li ve Xu (2013) yatırımcılar için bulanık rastgele getirilere sahip çok amaçlı portföy seçimi modelini getiri, risk ve likidite olmak üzere üç kritere bağlı olarak incelemişlerdir. Ning ve ark. (2013) üçgensel entropiyi bir kısıt olarak kullanarak belirsiz ortalama-varyans portföy optimizasyon problemini ele almışlardır.

Chen ve ark. (2017) güvenlik getirilerinin uzmanların tahminlerine göre öznel olarak verildiği ve belirsiz değişkenler olarak gösterildiği çeşitlendirilmiş portföy seçimi için bir yarı varyans yöntemi önermişlerdir. Portföy seçimi için en iyi tahsis planını genetik algoritmaya dayalı olarak belirlemişlerdir. Li ve ark. (2019) belirsizlik teorisini kullanarak bölünebilirlikli dinamik proje portföyü seçim problemini ele almışlardır. Geliştirdikleri matematiksel model yatırım hedef fonksiyonu ve finansal kaynak kısıtlamalarının riskini kontrol etmeyi amaçlamaktadır. Yadav ve ark. (2023) sezgisel bulanık bir çerçevede sürdürülebilir bir finansal portföy seçimi yaklaşımı önermişlerdir.

Bu çalışmada, finansal belirsizliklerden dolayı net ve kesin verilerle ifade edilemeyen beklenen getiri ve risk oranlarının kararsız bulanık elemanlar olarak ele alınarak yeni bir karasız bulanık portföy optimizasyonu modeli oluşturmak amaçlanmıştır. Bulanık matematiksel programlama temel alınarak yeni bir karasız bulanık matematiksel model geliştirilmiştir. Bu matematiksel model literatürde bulunmamaktadır ve belirsizlikleri geleneksel bulanık portföy optimizasyonu modeline göre daha kapsamlı tanımlayabilmektedir. Geleneksel bulanık matematiksel modelde kullanılan tek üyelik fonksiyonu yerine kararsız küme kavramına göre birden fazla üyelik derecesine sahiptir. Buna bağlı olarak oluşturulan model, yatırımcılara alternatif portföyler sunmaktadır. Bu da karar aşamasında karşılaştırma ve farklı yatırımlar yapma olanağına sahip olacak olan yatırımcıların lehine bir durum olacaktır. Çalışma kapsamında önerilen model, BIST 50 (Borsa İstanbul 50)'den elde edilen hisse senetleri kullanılarak çözülmüş ve çözümler yorumlanmıştır.

Literatürde getiri ve risk değerlerini kararsız bulanık elemanlar alarak modelleme yapan ve üyelik fonksiyonlarını farklı alt ve üst sınırlara göre tanımlayarak kurgulayan bir çalışmaya rastlanmamıştır. Çalışma bu yönüyle yenilik içermektedir. Ayrıca gerçek hayat verilerini kullanarak önerilen model çözülmüş ve portföy optimizasyonu yapılarak sonuçlar üç farklı tür risk yatırımcısı için yorumlanmıştır.

Çalışmanın ikinci bölümünde kararsız bulanık küme kavramı açıklanarak, karasız bulanık getiri ve risk verilerine sahip portföy optimizasyonu için geliştirilen matematiksel model sunulmuştur. Üçüncü bölümde önerilen modellerin BIST 50'de işlem görmüş olan birer aylık 30 adet hisse senedine ait verilerin günlük kapanış fiyatları alınarak uygulaması yapılmış ve sonuçlar yorumlanmıştır. Dördüncü bölüm ise sonuçlar sunulmuştur.

2. Materyal ve Yöntem

2.1. Kararsız Bulanık Kümeler ve Önerilen Matematiksel Model

Torra kararsız bulanık kümeleri tanımlarken, bulanık mantıkta bir kümeye ait olma derecesini belirten üyelik fonksiyonunun belirlemenin zorluğunu hataya bağlı olmadığını olası değerlerin birden fazla olabileceğini ve bunu bir küme ile belirtmek gerektiğini savunmuştur (Torra, 2010). Bu nedenle, Torra ve Narukawa, olası değerler kümesiyle üyeliği tanımlayabilmek için kararsız bulanık kümeleri önermişlerdir (Torra ve Narukawa, 2009). Kararsız bulanık küme kavramı Tanım 1 ile verilmiştir.

Tanım 1: X bir referans küme olsun, X üzerinde tanımlanan kararsız bulanık küme h fonksiyonu cinsinden ifade edilir. h fonksiyonu, X kümesini $[0,1]$ alt kümesine dönüşür. Kararsız bulanık kümenin her bir elemanı $h(x)$ sonlu ve boş olmayan $[0,1]$ aralığının bir alt kümesidir.

A kararsız bulanık kümesi $A = \{x, h_A(x) \,|x \in X\}$ matematiksel semboller ile verilir ve burada $h_A(x), x \in X$ olmak üzere A kümesinin olası üyelik derecelerini temsil eder. $h = h_A(x)$ kararsız bulanık eleman olarak adlandırılır (Xia ve Xu, 2011; Xu ve Xia, 2011).

Kolaylık olması açısından kararsız bulanık elemanlar $h_A(x) = \{\mu_1, \mu_2, \dots, \mu_l\}$ biçiminde tanımlanabilir. Bunlar kararsız bulanık kümenin elemanlarıdır. Burada μ_s $(s = 1,2, \dots, l)$ farklı üyelik fonksiyonlarını temsil eder. Dolayısıyla kararsız bulanık kümede l tane farklı üyelik fonksiyonu bulunmaktadır.

2.2. Geliştirilen Karasız Bulanık Portföy Matematiksel Modeli

Portföy optimizasyonu modelleri literatürde oldukça sıklıkla kullanılan modellemelerdir. İlk olarak Markowitz tarafından ortalama varyans modeli olarak geliştirilen model daha ilerleyen zamanlarda farklı risk ölçütleri kullanılarak modellenmiştir. Literatürde karesel programlamaya dayalı olarak modellenen Markowitz modeline alternatif olarak geliştirilen ortalama mutlak sapmayı risk ölçütü olarak kullanan Konno-Yamazaki modeli tercih edilen modeller arasında yer almaktadır

(Konno ve ark., 2002).

Ortalama mutlak sapmayı tabanlı Konno-Yamazaki portföy optimizasyonu modeli Eşitlik 1-7 ile verilmiştir. Getiri ve risk değerlerini nicel kesin değerler olarak alan model geleneksel Konno-Yamazaki modeli (GKYM) olarak adlandırılmıştır. Tablo 1 ile model içinde kullanılan simge, parametre ve karar değişkenleri tanımlanmıştır.

Tablo 1. Konno-Yamazaki matematiksel modeline ait simge, parametre ve karar değişkenleri

Simgeler	
n	Hisse senedi sayısı
j	Hisse senedi indisi $j = 1,2, \dots, n$
T	İncelenen dönem sayısı
t	T dönemi içerisinde herhangi bir dönem $t = 1,2, \dots, T$
Parametreler	
r_{jt}	j. hisse senedinin t döneminde gerçekleşen getiri oranı
r_j	j. hisse senedinin ortalama getiri oranı
a_{jt}	j. hisse senedinin t. dönem ve T dönemdeki ortalama getirisi arasındaki farktır. $a_{jt} = r_{jt} - r_j\ , j = 1,2, \dots, n\ , t = 1,2, \dots, T$
u_j	j. hisse senedine yapılan yatırım miktarının üst sınırı
μ_0	Toplam yatırım miktarı
ρ	Beklenen getiri oranı
ρM_0	Beklenen getiri miktarı
Karar Değişkenleri	
x_j	j. hisse senedine ait yatırım payı
y_t	Yardımcı değişken

GKYM yukarıdaki değişkenler yardımıyla aşağıdaki gibi modellenmiştir.

$$Min \sum_{t=1}^{T} y_t/T \quad (1)$$

Kısıtlar:

$$y_t - \sum_{j=1}^{n} a_{jt}x_j \geq 0\ , t = 1, \dots, T \quad (2)$$

$$y_t + \sum_{j=1}^{n} a_{jt}x_j \geq 0\ , t = 1, \dots, T \quad (3)$$

$$\sum_{j=1}^{n} r_j x_j \geq \rho M_0 \quad (4)$$

$$\sum_{J=1}^{n} x_j = M_0 \quad (5)$$

$$0 \leq x_j \leq u_j\ , j = 1, \dots, n \quad (6)$$

$$y_t \geq 0\ , t = 1, \dots, T \quad (7)$$

Bulanık matematiksel programlama, optimizasyon problemlerine bulanık mantık prensiplerini entegre eden bir yöntemdir. Bu yaklaşım, karar değişkenleri, kısıtlamalar ve amaç fonksiyonları gibi problemin çeşitli bileşenlerinin kesin değerlerden ziyade belirsiz, yaklaşık veya bulanık değerlerle ifade edildiği durumları ele almak için kullanılır. Bulanık matematiksel programlama, belirsiz verilerle çalışabilme ve çeşitli karar alternatiflerini değerlendirebilme yeteneği ile, karar verme süreçlerini daha esnek ve gerçekçi hale getirebilir (Lai ve ark., 1992).

Bulanık küme teorisinin uzantısı olarak kararsız bulanık kümeler kısa sürede birçok araştırmacı dikkatini tarafından benimsenmiştir. Bunun sebebi kararsızlık gerçek hayat problemlerinde sıklıkla karşılaşılan bir durumdur. Literatür incelendiğinde kararsız bulanık küme teorisinin uygulamalarının literatürde yaygın olduğu gözlenmiştir (Chen ve ark., 2013b; Liao ve Xu, 2015; Farhadinia, 2016; Ranjbar ve ark., 2018; Rodriguez ve ark., 2018)

Karasız Bulanık Matematiksel Programlama, bulanık matematiksel programlamanın genişletilmiş bir halidir ve özellikle karar problemlerinde belirsizliği ve karmaşıklığı daha iyi modellemeye odaklanır. Bu yaklaşım, özellikle belirsiz veya değişken koşullarla başa çıkmada kullanılan bir tekniktir (Wan ve ark., 2017).

Bu makalede, risk ve beklenen getiri değerleri karasız bulanık sayılar olan GKYM modelinin deterministik modele dönüştürülmesi ve uygulanması üzerine çalışılmıştır. eşitlik 1-7 ile verilen matematiksel modelde ρM_0 ile verilen sağ taraf sabiti ve amaç fonksiyonu kararsız bulanık sayı olması durumunda elde edilen doğrusal programlama problemi eşitlik 8-10 ile verilmiştir. Bu model Kararsız Bulanık Konno Yamazaki Modeli (KBKYM) olarak adlandırılmıştır.

$$Enb\ \alpha \quad (8)$$

Kısıtlar

(2-3)

$$\mu_{0s}(y) \geq \alpha, s = 1,2 \dots, l \quad (9)$$

$$\mu_{1s}(r) \geq \alpha, s = 1,2 \dots, l \quad (10)$$

(5-7)

GKYM modelinde, amaç fonksiyonu ve sağ taraf sabitlerinde kararsız bulanık parametreler içeren kararsız bulanık model, KBKYM ile çözülebilir. Eşitlik 9 ve 10 sırasıyla kararsız bulanık sayılar içeren risk ve beklenen getiriye ait üyelik fonksiyonlarını göstermektedir. Bu çalışmada kararsız eleman sayısı 3 alınmış ve s=1, 2, 3 için üyelik fonksiyonlarının açık halleri eşitlik 11-13 ile verilmiştir.

$$\mu_{01}(y) = \begin{cases} 1, & \sum_{t=1}^{T} y_t/T < z_L - (k * z_L) \\ 1 - \frac{[\sum_{t=1}^{T} y_t/T] - (z_L - (k*z_L))}{(z_U - z_L) - k*(z_U - z_L)}, & z_L - (k * z_L) \leq \sum_{t=1}^{T} y_t/T \leq z_U - (k * z_U) \\ 0, & \sum_{t=1}^{T} y_t/T > z_U - (k * z_U) \end{cases} \quad (11)$$

$$\mu_{02}(y)=\begin{cases}1, & \sum_{t=1}^{T} y_t/T < z_L \\ 1-\frac{[\sum_{t=1}^{T} y_t/T]-z_L}{(z_U-z_L)}, & z_L \le \sum_{t=1}^{T} y_t/T \le z_U \\ 0, & \sum_{t=1}^{T} y_t/T > z_U\end{cases} \quad (12)$$

$$\mu_{03}(y)=\begin{cases}1, & \sum_{t=1}^{T} y_t/T < z_L+(k*z_L) \\ 1-\frac{[\sum_{t=1}^{T} y_t/T]-(z_L+(k*z_L))}{(z_U-z_L)+k*(z_U-z_L)}, & z_L+(k*z_L) \le \sum_{t=1}^{T} y_t/T \le z_U+(k*z_U) \\ 0, & \sum_{t=1}^{T} y_t/T > z_U+(k*z_U)\end{cases} \quad (13)$$

Burada z_U, GKYM modelinin optimal çözünden elde edilen y_t, $t=1,\dots,T$ karar değişkenlerine bağlı olarak elde edilmiş ve $z_U=\max_t y_t$ olarak belirlenmiştir. z_L, GKYM modelinin en iyi değeridir. Kararsız bulanık elemanları oluşturan 3 adet üyelik fonksiyonu, $s=1,2,3$ olmak üzere k =0,10; 0,20;…,0,90 oranları için çalışılmıştır (eşitlik 14).

$$\mu_{1s}(r)=\begin{cases}0, & \sum_{J=1}^{n} r_j x_j < \left(L_{\rho M_0}\right)_s, s=1,2,3 \\ 1-\frac{\left(U_{\rho M_0}\right)_s-\sum_{j=1}^{n} r_j x_j}{\left(U_{\rho M_0}-L_{\rho M_0}\right)_s}, & \left(L_{\rho M_0}\right)_s \le \sum_{J=1}^{n} r_j x_j \le \left(U_{\rho M_0}\right)_s, s=1,2,3 \\ 1, & \sum_{J=1}^{n} r_j x_j > \left(U_{\rho M_0}\right)_s, \ s=1,2,3\end{cases} \quad (14)$$

$\mu_{1s}(r), s=1,2,3$ üyelik fonksiyonlarını oluşturmak için, beklenen getiri değerlerinin yani ρM_0'ların farklı güven düzeylerindeki güven aralıklarından yararlanılmıştır. Burada L ve U notasyonları güven aralıklarının alt ve üst güven seviyeleridir. Güven aralıkları oluşturulurken güven düzeylerinin yüksek olması istatistiksel analizlerde istenilen bir durumdur. Bu sebeple, çalışma kapsamında üç farklı güven seviyesi kullanılmış olup bunlar $s=$ 1 için 0,90; $s=2$ için 0,95; $s=3$ için 0,99'dır. Güven aralıkları oluşturulurken veri setinin özelliğine ve varsayım sınamalarına göre t veya z dağılımına bağlı olarak hesaplamalar yapılmıştır. Güven aralıkları eşitlik 15 ve 16 ile hesaplanmıştır.

$$P\left(\overline{X_{\rho M_0}}+z_{\alpha/2}\left(\frac{\sigma_{\rho M_0}}{\sqrt{n}}\right)<\mu_{\rho M_0}<\overline{X_{\rho M_0}}+z_{\alpha/2}\left(\frac{\sigma_{\rho M_0}}{\sqrt{n}}\right)\right)=1-\alpha' \quad (15)$$

$$P\left(\overline{X_{\rho M_0}}+t_{\alpha/2}\left(\frac{S_{\rho M_0}}{\sqrt{n}}\right)<\mu_{\rho M_0}<\overline{X_{\rho M_0}}+t_{\alpha/2}\left(\frac{S_{\rho M_0}}{\sqrt{n}}\right)\right)=1-\alpha' \quad (16)$$

Burada, α' anlamlılık düzeyidir. Yukarıda verilen açıklamalar sonucunda, Eşitlik (8-10) ile oluşturulan doğrusal programlama problemi en iyi çözümü tek olan kesin doğrusal matematiksel modele dönüşmektedir.

3. Bulgular ve Tartışma

Bu bölümde Bölüm 2'de önerilen kararsız bulanık portföy optimizasyonu matematiksel modelinin gerçek bir uygulaması yapılmıştır. Borsa İstanbul (BIST 50)'da yer alan hisse senetlerinin her bir aylık dönem için 30 aya ait günlük kapanış değerleri alınarak, önerilen kararsız bulanık programlama model sonuçlarına bağlı olarak portföy seçenekleri belirlenmiştir.

Öncelikle KBKYM'nde Eşitlik (9-10) kısıtlarındaki üyelik fonksiyonlarını oluşturmak için farklı k değerleri ve güven düzeyleri belirlenmiştir. Eşitlik (11-13) ile verilen üyelik fonksiyonları kararsız bulanık risk değerlerine ait fonksiyonu tanımlamakta olup alternatif seçeneklerde tüm ayırtıları görebilmek amacıyla (0-1) aralığında 0,1 artışla k = 0,1; 0,2; …; 0,9 değerleri için model çözümleri elde edilmiştir. Eşitlik (14) ile verilen üyelik fonksiyonu kararsız bulanık getiri değerlerinin fonksiyonu olup KBKYM'nde 0,9; 0,95 ve 0,99 olmak üzere üç farklı güven seviyesinde çalışılmıştır. Buna göre 30 ay için elde edilen çözümler Tablo 2'de verilmiştir.

Tablo 2'de her bir satır farklı bir aylık döneme ait günlük kapanış değerlerinin 30 farklı aya ait günlük kapanış değerlerini kullanarak oluşturulan model sonuçlarından elde edilen getiri, risk ve atama yapılan hisse senedi sayılarını (HSS) göstermektedir. Burada, A1 birinci aya ait bir aylık günlük kapanış değerlerini kullanarak oluşturulan modeli, A2 ikinci aya ait bir aylık günlük kapanış değerlerini kullanarak oluşturulan modeli temsil etmektedir. Dolayısıyla, 30. aya ait problem, A30 ile notasyonlandırılmıştır.

Örneğin A1 problemi için, $z_U=0{,}0623$ ve $z_L=0{,}0064$ olup, $k=0{,}1$ ve $s=1,2,3$ için kararsız bulanık risklere ait, kararsız bulanık elemanların üyelik fonksiyonları $\mu_{01}(y)$, $\mu_{02}(y)$, $\mu_{03}(y)$ ile gösterilmiştir ve eşitlik 17-19 ile gösterilmiştir.

$$\mu_{01}(y)=\begin{cases}1, & \sum_{t=1}^{T} y_t/22 \ < 0{,}0064 \ -(0{,}1*0{,}0064\ )\\ 1-\frac{[\sum_{t=1}^{T} y_t/22]-(0{,}0064\ -(0{,}1*0{,}0064\ ))}{(0{,}0623\ -0{,}0064\ )-0{,}1*(0{,}0623\ -0{,}0064\ )}, & 0{,}0064\ -(0{,}1*0{,}0064\ ) \le \sum_{t=1}^{T} y_t/22 \ \le 0{,}0623\ -(0{,}1*0{,}0623\ )\\ 0, & \sum_{t=1}^{T} y_t/22 > 0{,}0623\ -(0{,}1*0{,}0623\ )\end{cases} \quad (17)$$

$$\mu_{02}(y)=\begin{cases}1, & \sum_{t=1}^{T} y_t/22 \ < 0{,}0064\\ 1-\frac{[\sum_{t=1}^{T} y_t/22]-0{,}0064}{(0{,}0623\ -0{,}0064)}, & 0{,}0064 \le \sum_{t=1}^{T} y_t/22 \ \le 0{,}0623\\ 0, & \sum_{t=1}^{T} y_t/22 > \ 0{,}0623\end{cases} \quad (18)$$

$$\mu_{03}(y)=\begin{cases}1, & \sum_{t=1}^{T} y_t/22 \ < 0{,}0064+(0{,}1*0{,}0064)\\ 1-\frac{[\sum_{t=1}^{T} y_t/22]-(0{,}0064+(0{,}1*0{,}0064))}{(0{,}0623\ -0{,}0064)+0{,}1*(0{,}0623\ -0{,}0064)}, & 0{,}0064+(0{,}1*0{,}0064) \le \sum_{t=1}^{T} y_t/22 \ \le 0{,}0623\ +(0{,}1*0{,}0623\ )\\ 0, & \sum_{t=1}^{T} y_t/22 > 0{,}0623\ +(0{,}1*0{,}0623\ )\end{cases} \quad (19)$$

Tablo 2. Kararsız bulanık doğrusal programlama modeli sonuçları

	$k=0{,}1$				$k=0{,}2$				$k=0{,}3$			
A.No	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS
A1	0,9015	0,0328	0,0107	18	0,8838	0,0309	0,0103	18	0,8628	0,0286	0,0098	18
A2	0,6060	-0,0048	0,0000	20	0,6058	-0,0048	0,0000	22	0,6059	-0,0048	0,0000	22
A3	0,9407	0,0306	0,0093	18	0,9189	0,0289	0,0090	18	0,8922	0,0269	0,0086	18
A4	1,0000	0,0591	0,0000	23	0,9818	0,0560	0,0000	22	0,9793	0,0560	0,0000	22
A5	0,8379	0,0280	0,0039	21	0,8223	0,0262	0,0037	21	0,8046	0,0242	0,0034	21
A6	0,9616	0,0166	0,0041	22	0,9459	0,0151	0,0040	22	0,9262	0,0133	0,0040	22
A7	0,7700	0,0471	0,0041	22	0,7515	0,0453	0,0038	22	0,7309	0,0433	0,0036	22
A8	0,8995	0,0428	0,0033	20	0,8795	0,0412	0,0032	20	0,8552	0,0393	0,0031	20
A9	0,7262	0,0455	0,0030	22	0,7078	0,0436	0,0028	22	0,6877	0,0415	0,0026	22
A10	0,8797	0,0564	0,0033	22	0,8642	0,0551	0,0031	22	0,8464	0,0535	0,0030	22
A11	0,7099	-0,0138	0,0032	21	0,6907	-0,0160	0,0030	21	0,6695	-0,0183	0,0028	21
A12	0,6237	0,0322	0,0000	22	0,6236	0,0322	0,0000	22	0,6235	0,0322	0,0000	22
A13	0,9807	0,0534	0,0091	19	0,9666	0,0521	0,0090	19	0,9486	0,0505	0,0090	19
A14	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23
A15	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23
A16	0,9207	0,2657	0,0524	18	0,9046	0,2576	0,0507	20	0,8818	0,2462	0,0496	21
A17	0,9111	0,2531	0,0061	22	0,9012	0,2488	0,0057	22	0,8901	0,2441	0,0053	22
A18	0,9936	0,1753	0,0000	23	0,9755	0,1690	0,0000	23	0,9721	0,1678	0,0000	23
A19	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23
A20	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23
A21	0,7895	0,0263	0,0301	20	0,7696	0,0168	0,0285	21	0,7464	0,0057	0,0267	21
A22	0,8339	-0,1483	0,0245	21	0,8139	-0,1578	0,0234	21	0,7900	-0,1693	0,0222	21
A23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23
A24	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23
A25	0,9226	-0,0633	0,0000	23	0,9166	-0,0671	0,0000	23	0,9121	-0,0699	0,0000	23
A26	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23
A27	0,8848	-0,0925	0,0098	21	0,8745	-0,0981	0,0091	21	0,8624	-0,1048	0,0084	21
A28	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23
A29	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23
A30	0,8144	-0,2108	0,0220	20	0,7999	-0,2171	0,0205	21	0,7812	-0,2252	0,0191	22
	$k=0{,}4$				$k=0{,}5$				$k=0{,}6$			
A.No	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS
A1	0,8377	0,0259	0,0093	18	0,8069	0,0226	0,0086	18	0,7685	0,0184	0,0077	18
A2	0,6057	-0,0048	0,0000	22	0,6056	-0,0048	0,0000	22	0,6054	-0,0048	0,0000	22
A3	0,8546	0,0241	0,0083	19	0,7930	0,0194	0,0082	19	0,7040	0,0127	0,0080	19
A4	0,9489	0,0560	0,0000	22	0,9703	0,0560	0,0000	22	0,9629	0,0560	0,0000	22
A5	0,7846	0,0218	0,0031	21	0,7600	0,0190	0,0028	21	0,7118	0,0135	0,0026	21
A6	0,9005	0,0109	0,0039	21	0,8655	0,0077	0,0038	21	0,8148	0,0030	0,0037	21
A7	0,7067	0,0409	0,0032	21	0,6759	0,0379	0,0029	21	0,6375	0,0341	0,0025	21
A8	0,8249	0,0369	0,0030	20	0,7860	0,0338	0,0028	20	0,7343	0,0297	0,0027	20

Tablo 2. Kararsız bulanık doğrusal programlama modeli sonuçları (devamı)

	$k = 0{,}4$				$k = 0{,}5$				$k = 0{,}6$			
A.No	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS
A9	0,6652	0,0391	0,0023	22	0,6400	0,0365	0,0020	22	0,6118	0,0336	0,0017	22
A10	0,8239	0,0515	0,0028	21	0,7953	0,0490	0,0025	21	0,7562	0,0456	0,0023	21
A11	0,6460	-0,0210	0,0025	21	0,6194	-0,0239	0,0022	22	0,5890	-0,0273	0,0019	22
A12	0,6235	0,0322	0,0000	22	0,6234	0,0322	0,0000	22	0,6224	0,0321	0,0000	23
A13	0,9251	0,0484	0,0089	19	0,8929	0,0455	0,0088	19	0,8458	0,0412	0,0086	18
A14	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23
A15	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23
A16	0,8528	0,2317	0,0481	21	0,8150	0,2128	0,0462	21	0,7628	0,1868	0,0438	22
A17	0,8777	0,2387	0,0048	22	0,8638	0,2328	0,0042	22	0,8465	0,2254	0,0036	21
A18	0,9447	0,1582	0,0000	23	0,9604	0,1637	0,0000	23	0,9507	0,1603	0,0000	23
A19	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23
A20	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23
A21	0,7194	-0,0072	0,0246	21	0,6879	-0,0223	0,0222	21	0,6490	-0,0410	0,0195	21
A22	0,7617	-0,1829	0,0207	21	0,7277	-0,1991	0,0190	21	0,6861	-0,2191	0,0169	21
A23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23
A24	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23
A25	0,9020	-0,0764	0,0000	23	0,8962	-0,0801	0,0000	23	0,8767	-0,0925	0,0000	23
A26	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23
A27	0,8470	-0,1132	0,0077	21	0,8294	-0,1228	0,0068	21	0,8089	-0,1341	0,0059	20
A28	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23
A29	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23
A30	0,7587	-0,2349	0,0175	22	0,7329	-0,2461	0,0157	22	0,6984	-0,2611	0,0137	22
	$k = 0{,}7$				$k = 0{,}8$				$k = 0{,}9$			
A.No	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS	Alfa	Getiri	Risk	HSS
A1	0,6924	0,0102	0,0071	21	0,5363	-0,0066	0,0065	20	0,0407	-0,0414	0,0060	21
A2	0,6053	-0,0049	0,0000	22	0,6053	-0,0049	0,0000	22	0,6002	-0,0050	0,0000	22
A3	0,5396	0,0127	0,0080	19	0,2108	0,0127	0,0080	19	0,0000	0,0104	0,0048	19
A4	0,8949	0,0560	0,0000	22	0,8424	0,0560	0,0000	22	0,5181	0,0560	0,0000	22
A5	0,6450	0,0058	0,0023	22	0,5457	-0,0056	0,0018	22	0,3352	-0,0227	0,0013	22
A6	0,7362	-0,0043	0,0036	21	0,5879	-0,0180	0,0033	21	0,1141	-0,0380	0,0032	20
A7	0,5872	0,0291	0,0021	21	0,5246	0,0230	0,0016	21	0,4107	0,0151	0,0009	20
A8	0,6623	0,0240	0,0024	20	0,5513	0,0152	0,0020	21	0,2710	-0,0001	0,0015	22
A9	0,5798	0,0303	0,0014	22	0,5320	0,0253	0,0010	22	0,3922	0,0150	0,0006	22
A10	0,6932	0,0400	0,0020	22	0,5850	0,0305	0,0017	22	0,1040	0,0283	0,0017	21
A11	0,5545	-0,0311	0,0015	22	0,5151	-0,0355	0,0011	22	0,4532	-0,0405	0,0006	22
A12	0,6206	0,0319	0,0000	23	0,5863	0,0287	0,0000	23	0,5679	0,0270	0,0000	23
A13	0,7650	0,0339	0,0085	20	0,5992	0,0294	0,0085	19	0,0983	0,0294	0,0085	19
A14	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23	0,8577	-0,0060	0,0000	23
A15	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23	1,0000	0,0208	0,0000	23
A16	0,6865	0,1486	0,0402	22	0,5654	0,0881	0,0347	21	0,1597	-0,0505	0,0305	20
A17	0,7667	0,2205	0,0036	21	0,6000	0,2205	0,0036	21	0,1003	0,2205	0,0036	21
A18	0,8875	0,1512	0,0000	22	0,8312	0,1512	0,0000	22	0,5195	0,1512	0,0000	22
A19	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23	1,0000	-0,0065	0,0000	23
A20	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23	0,6656	-0,1419	0,0000	23
A21	0,5953	-0,0666	0,0163	22	0,5271	-0,0993	0,0124	22	0,4084	-0,1396	0,0075	22
A22	0,6294	-0,2462	0,0144	21	0,5414	-0,2884	0,0114	22	0,3536	-0,3519	0,0076	22
A23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23	1,0000	-0,0050	0,0000	23
A24	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23	0,9323	-0,1520	0,0000	23
A25	0,8474	-0,1111	0,0000	23	0,7998	-0,1414	0,0000	23	0,5403	-0,1946	0,0000	22
A26	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23	1,0000	0,1869	0,0000	23
A27	0,7669	-0,1548	0,0050	20	0,6004	-0,1548	0,0050	20	0,1008	-0,1548	0,0050	20
A28	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23	1,0000	0,4203	0,0000	23
A29	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23	0,9333	-0,0309	0,0000	23
A30	0,6438	-0,2848	0,0117	21	0,5479	-0,3264	0,0094	22	0,3314	-0,3928	0,0066	22

A1 probleminde kararsız bulanık getirilere ait, $s = 1$ için $U_{\rho M_0} = 0{,}0231$ ve $L_{\rho M_0} = -0{,}0441$ $s = 2$ için $U_{\rho M_0} = 0{,}0298$ ve $L_{\rho M_0} = -0{,}0508$ ve $s = 3$ için $U_{\rho M_0} = 0{,}0434$ ve $L_{\rho M_0} = -0{,}0644$ hesaplanmış ve kararsız bulanık elemanları oluşturulan üç üyelik fonksiyonu eşitlik 20-22 ile verilmiştir.

$$\mu_{11}(r) = \begin{cases} 0, & \sum_{J=1}^{n} r_j x_j < -0{,}0441 \\ 1 - \frac{0{,}0231 - \sum_{j=1}^{n} r_j x_j}{0{,}0231 + 0{,}0441}, & -0{,}0441 \le \sum_{J=1}^{n} r_j x_j \le 0{,}0231 \\ 1, & \sum_{J=1}^{n} r_j x_j > 0{,}0231 \end{cases} \quad (20)$$

$$\mu_{12}(r) = \begin{cases} 0, & \sum_{J=1}^{n} r_j x_j < -0{,}0508 \\ 1 - \frac{0{,}0298 - \sum_{j=1}^{n} r_j x_j}{0{,}0298 + 0{,}0508}, & -0{,}0508 \le \sum_{J=1}^{n} r_j x_j \le 0{,}0298 \\ 1, & \sum_{J=1}^{n} r_j x_j > 0{,}0298 \end{cases} \quad (21)$$

$$\mu_{13}(r) = \begin{cases} 0, & \sum_{J=1}^{n} r_j x_j < -0{,}0644 \\ 1 - \frac{0{,}0434 - \sum_{j=1}^{n} r_j x_j}{0{,}0434 + 0{,}0644}, & -0{,}0644 \le \sum_{J=1}^{n} r_j x_j \le 0{,}0434 \\ 1, & \sum_{J=1}^{n} r_j x_j > 0{,}0434 \end{cases} \quad (22)$$

Tablo 2'de A1 problem sonuçları incelendiğinde, amaç fonksiyonu değeri olan alfa 0,901517, getiri değeri 0,032779, risk değeri ise 0,010707 elde edilmiştir. Bu çözüme karşılık gelen 50 hisse senedi içerisinden yatırım yapılan hisse senedi sayısı 18 bulunmuştur. Ayrıca, A1 probleminde k=0,2 alınarak bulunan çözüm sonuçlarında, alfa değerinin 0,883769 seviyesine, getiri değerinin 0,030865 seviyesine, risk değerinin 0,010311 olup azalma gösterdiği izlenmiştir.

30 aylık veri üzerinden alınan tüm çözümlerin her k değerleri için elde edilen alfa, getiri ve risk değerlerinin ortalaması alınmıştır. Her k değeri için hesaplanan ortalama alfa, ortalama getiri ve ortalama risk değerleri Tablo 3 ile özetlenmiştir.

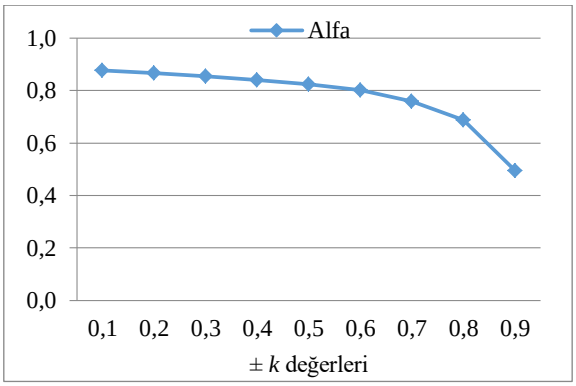
Tablo 3. k değerlerine göre alfa, getiri ve risk ortalamaları

	Ort Alfa	Ort Getiri	Ort Risk	MS Oranı*
$k = 0{,}1$	0,876566	0,030569	0,006627	4,484473
$k = 0{,}2$	0,866240	0,028123	0,006333	4,306828
$k = 0{,}3$	0,855254	0,025547	0,006033	4,093883
$k = 0{,}4$	0,840001	0,022063	0,005693	3,726157
$k = 0{,}5$	0,824540	0,018514	0,005299	3,333449
$k = 0{,}6$	0,801075	0,013278	0,004837	2,569498
$k = 0{,}7$	0,759612	0,005875	0,004338	1,158430
$k = 0{,}8$	0,687455	-0,003822	0,003733	-1,251440
$k = 0{,}9$	0,493611	-0,019774	0,002998	-6,879261

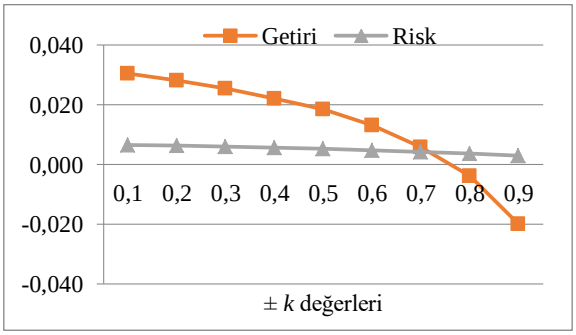
Ort= ortalama, MS= modifeye sharpe, *Risksiz faiz oranı %0,085 alınmıştır.

k'nın farklı değerleri için elde edilen çözümlerdeki alfa, getiri ve risk değerlerinin grafikleri sırasıyla Şekil 1 ve Şekil 2 ile verilmiştir. Her iki grafikte incelendiğinde, k değeri arttıkça alfa, getiri ve risk değerlerinin birlikte azaldığı görülmektedir.

Grafikler incelendiğinde, k değeri arttıkça alfa, getiri ve risk değerlerinin birlikte azaldığı görülmektedir. Bu durumda k değeri küçük alındığında, riskin yüksek ve getirinin yüksek olduğu yatırım seçenekleri bulunurken, k değeri büyük alındığında ise riskin düşük ve getirinin düşük seviyede olduğu yatırım seçenekleri elde edilmektedir.



Şekil 1. k değerlerinin alfaya göre değişimi.



Şekil 2. k değerlerinin getiri ve risk oranlarına göre değişimi.

Tablo 2'de verilen tüm sonuçlar ve bu sonuçlardan hesaplanan ortalama getiri ve ortalama risk değerleri üzerinden çizilen grafikler birlikte değerlendirildiğinde, riskten kaçınan yatırımcı, sharpe oranı en düşük olan ve k değerinin yüksek olduğu (k = 0,7; k = 0,8 ve k = 0,9)

model sonuçlarını kullanarak yatırım yapabilirler. Bu sonuçlarda risk ve getiri en düşük seviyesindedir. Risk arayan yatırımcı, sharpe oranı en yüksek olan ve k değerinin düşük alındığı (k = 0,1; k = 0,2 ve k = 0,3) model sonuçlarına göre yatırım yapabilirler. Bu portföy seçeneklerinde risk ve getiri en yüksek seviyesindedir. Riske karşı nötr olan yatırımcı ise, diğer k değerleri (k = 0,4; k = 0,5 ve k = 0,6) için elde edilen model sonuçlarını kullanabilirler.

4. Sonuç

Bu çalışmada, literatürdeki mevcut modellerin temel öncülüğünde belirsiz risk ve getiri oranlarının bulunduğu kararsız bulanık portföy optimizasyonu için matematiksel model önerilmektedir. Portföy seçiminin yatırımcılar için oldukça güç olmasının temel nedeni belirsizlik ve buna bağlı olarak parametrelerin net olmamasına bağlı olmasıdır. Bununla birlikte bu makalede önerilen modelin çözümleri sonucunda, alternatif hisse senedi atamaları ve oranları elde edilmiştir. Bu sayede öncelikleri farklı olan yatırımcıların olası seçenekler içerisinden kendilerine en uygun olan hisse senedine yatırım yapmalarına olanak sağlanabilir.

Finansal piyasaların zaman zaman dalgalanması nedeniyle, bazı finansal değişkenler her zaman kesin sayılarla ifade edilemeyebilir bu durumunda çalışma kapsamında önerilen kararsız bulanık portföy matematiksel modeli uygun bir araç olarak literatüre katkı sağlayabilir.

Önerilen model, geleneksel yöntemlerle çözülemeyen ve finansal parametrelerdeki farklılaşmalardan kaynaklı belirsizliklerle başa çıkmak için özel bir olasılık sunar. Bu model ve sonuçları hem teorisyenler hem de uygulayıcılar için uygun bir araç olabilir.

Çalışma kapsamında önerilen yöntemin literatüre sağladığı katkılar ve içerdiği yenilikler aşağıda maddeler halinde özetlenmiştir.

1. Önerilen matematiksel model, mevcut veriler ve/veya firmalardan/diğer kurumlardan gelen raporlar yetersiz bilgiye sahip olduğunda bilgi eksikliği ile başa çıkmak amacıyla kullanılabilir. Yatırımcının risk ve getiriye bakış açısına bağlı olarak farklı alternatiflerin kurgulanması ve kendisine göre en iyi portföy seçiminin oluşturulabilmesi için kapsamlı bir çerçeve sağlar.
2. Yatırımcıların kişisel tercihlerine göre sonuçların elde edilebilmesine olanak sağlayan modelde kararsız bulanık küme kuramına bağlı olarak birden fazla üyelik derecesine sahip olarak modellenen ve literatürde bulunmayan yeni bir karasız bulanık portföy optimizasyonu modeli sunulmuştur.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	T.D.	M.G.K.	K.D.A.
K	50	20	30
T	40	30	30
Y	40	25	35
VTI	50	30	20
VAY	40	30	30
KT	40	35	25
YZ	40	25	35
KI	40	30	30
GR	50	20	30
PY	50	25	35
FA	40	30	30

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

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ÖLÜMCÜL OLMAYAN ANTİBİYOTİK DOZLARININ *Aeromonas veronii* ÜZERİNDEKİ ETKİLERİNİN ARAŞTIRILMASI

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Özet: Antibiyotikler, genellikle bakteriyel hastalıkların tedavisinde geniş çapta kullanılan farmasötik ajanlardır. Ancak, son yıllarda antibiyotiklerin kontrolsüz ve yanlış kullanımı, bakterilerin birçok farklı ortamda öldürücü olmayan sub-minimum inhibisyon konsantrasyonlarına (sub-MİK) maruz kalmasına neden olmuştur. Bu durum, antibiyotiklerin bakterilerin virülans faktörleri üzerindeki etkilerini anlamak açısından kritik bir önem taşımaktadır. Sub-MİK seviyelerdeki antibiyotikler, bakteriyel virülans ve direnç mekanizmalarını etkileyerek, enfeksiyon kontrolü ve tedavi stratejilerini yeniden değerlendirmeyi gerektirir. Bu çalışmada, bir tatlı su kaynağından izole edilen *Aeromonas veronii* izolatının klinikte yaygın olarak kullanılan antibiyotiklere karşı antimikrobiyal duyarlılığı değerlendirilmiş ve duyarlı olduğu antibiyotikler için MİK değerleri belirlenmiştir. Ayrıca, antibiyotiklerin sub-MİK (MİK/2 ve MİK/4) dozlarının bakterinin biyofilm oluşturma kapasitesiyle morfolojisi üzerindeki etkileri incelenmiştir. Sonuçlar, *A. veronii*'nin çalışmada kullanılan 14 antibiyotikten 4'üne (ampisilin, seftazidim, seftriakson ve trimetoprim-sülfametoksazol) direnç gösterdiğini ortaya koymuştur. Ayrıca sub-MİK'lerin biyofilm oluşumunu azalttığı, siprofloksasinin uzun filamentli, meropenemin ise yuvarlak hücre morfolojisine neden olduğu gözlemlenmiştir. Bu bulgular, antibiyotiklerin sub-MİK'lerinin bakteriyel virülans ve morfolojik özellikler üzerindeki etkilerini aydınlatmakta ve bu etkilerin klinik ve çevresel antibiyotik yönetiminde göz önünde bulundurulması gerektiğini vurgulamaktadır. Bu tür çalışmalar, antibiyotik direncinin önlenmesi ve tedavi stratejilerinin geliştirilmesi açısından büyük önem taşımaktadır.

Anahtar kelimeler: *Aeromonas veronii*, Antibiyotik, Bakteriyel morfoloji, Biyofilm, Sub-MİK

Investigation of the Effects of Non-Lethal Antibiotic Doses on *Aeromonas veronii*

Abstract: Antibiotics are widely used pharmaceutical agents for the treatment of bacterial diseases in general. However, in recent years, the uncontrolled and incorrect use of antibiotics has led to bacteria being exposed to non-lethal sub-minimum inhibitory concentrations (sub-MIC) in various environments. This situation is critically important for understanding the effects of antibiotics on bacterial virulence factors. Antibiotics at sub-MICs affect bacterial virulence and resistance mechanisms, necessitating a revaluation of infection control and treatment strategies. In this study, the antimicrobial susceptibility of *Aeromonas veronii* isolate, isolated from a freshwater source, to antibiotics commonly used in clinical practice was evaluated, and MICs were determined for the antibiotics to which it was sensitive. Additionally, the effects of sub-MIC (MIC/2 and MIC/4) doses of antibiotics on the bacterium's biofilm formation capacity and morphology were investigated. The results revealed that *A. veronii* was resistant to 4 out of 14 antibiotics tested in the study (ampicillin, ceftazidime, ceftriaxone, and trimethoprim-sulfamethoxazole). Furthermore, sub-MICs were observed to reduce biofilm formation, with ciprofloxacin causing long filamentous morphology and meropenem resulting in a round cell morphology. These findings shed light on the effects of sub-MIC antibiotics on bacterial virulence and morphological characteristics and emphasize that these effects should be considered in clinical and environmental antibiotic management. Such studies are of great importance in preventing antibiotic resistance and developing treatment strategies.

Keywords: *Aeromonas veronii*, Antibiotics, Bacterial morphology, Biofilm, Sub-MIC

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1. Giriş

Antibiyotikler, patojenlerin neden olduğu hastalıkların tedavisinde oldukça önemlidir. Antibiyotiklerin hem tarımsal hem de tıbbi amaçlarla aşırı kullanımı, bakterilerin minimum inhibisyon konsantrasyonlarından (MİK) daha düşük antibiyotik dozlarına (sub-MİK) sürekli olarak maruz kalmasına yol açmaktadır (Liu ve ark., 2021). Bu antibiyotik dozları bakterilerde fenotipik ve genotipik değişikliklere neden olabilmekte, sinyal molekülleri olarak hareket edebilmekte ve bakterilerin fizikokimyasal özelliklerini ve virülans genlerinin ekspresyonunu değiştirebilmektedir (Narimisa ve ark., 2020). Son çalışmalar, sub-MİK antibiyotiklerin bakterilerde morfolojik değişikliklere, biyofilm oluşturma kapasitesinde artışa, bakteriyel yapışma kapasitesinde artışa ve dış membran proteinlerinin aşırı ekspresyonuna neden olabileceğini göstermiştir (Dhabaan ve ark., 2016; Chadha ve Khullar, 2021; Chen

ve ark., 2021; Delik ve ark., 2023; Opstrup ve ark., 2023; Delik ve ark., 2024). Bakteri hücrelerindeki bu değişiklikler antibiyotiklere karşı direnç gelişimini teşvik edebilmektedir. Bu nedenle, bakterilerde çoklu antibiyotik direnci gelişimini önlemek ve hastalıkların tedavisinde doğru antibiyotik kullanım stratejilerini belirlemek için bakterilerin antimikrobiyal direnç profillerinin belirlenmesi ve sub-MİK'lerin bakteriler üzerindeki etkilerinin daha iyi anlaşılması gerekmektedir.

Aeromonas veronii, Aeromonadaceae ailesine ait bir Gram-negatif bakteri türüdür ve çeşitli çevresel ortamlarda, özellikle tatlı su ekosistemlerinde bulunur. Ayrıca, hem insanlarda hem de hayvanlarda enfeksiyonlara neden olabilmektedir. İnsanlarda, genellikle bağırsak enfeksiyonları, yara enfeksiyonları ve sepsis gibi çeşitli klinik tablolarla ilişkilidir (Pereira ve ark., 2008; Janda ve Abbott, 2010). Bu bakteri özellikle antibiyotiklere karşı yüksek direnç gösterebilen bir türdür. Beta-laktam antibiyotikler, aminoglikozidler ve kinolonlar gibi çeşitli antimikrobiyal ajanlara karşı direnç geliştirebilir. Bu özellikleri, özellikle bağışıklık sistemi zayıf olan bireylerde ve hastane ortamlarında ciddi enfeksiyon riskleri oluşturur (Yuwono ve ark., 2021). Ayrıca, biyofilm oluşturma yeteneği bakterinin çevresel koşullara ve antibiyotik tedavisine karşı direncini artırabilir. Bu durum, *A. veronii*'nin tedavisinde zorluklar yaratarak enfeksiyonların yayılmasını kolaylaştırabilmektedir. *A. veronii*'nin su kaynaklarından ve hayvanlardan insanlara bulaşabilmesi, çevresel sağlık ve halk sağlığı açısından önemlidir. Bu bakterinin doğasal ortamları arasında tatlı su göletleri, nehirler ve akarsular bulunur ve bu ortamlarda bakteriyel kontaminasyon riskleri göz önüne alınmalıdır (Ghenghesh ve ark., 2008).

Gerçekleştirilen bu çalışmada, bir tatlı su kaynağından (Antalya Boğaçay) *A. veronii* izole edilerek tanımlanmıştır. Bakterinin 14 antibiyotiğe karşı antimikrobiyal duyarlılığı belirlenerek duyarlı olduğu antibiyotikler için MİK değerleri araştırılmıştır. Ayrıca, sub-MİK'lerdeki antibiyotiklerin bakteri hücre morfolojisi ve biyofilm oluşturma kapasitesi üzerindeki etkisi belirlenmiştir.

2. Materyal ve Yöntem

2.1. Su Örneklerinin Toplanması ve Bakteri İzolasyonu

Bu çalışmada kullanılan su örnekleri 2021 yılında Antalya (Türkiye) ilinde sık insan faaliyetleri (yüzme ve balık tutma gibi) nedeniyle önemli olan ve tarım arazilerinin sulanmasında kullanılan bir tatlı su kaynağından (Boğaçay) izole edilmiştir (coğrafi koordinatlar 36°51′12.5″K 30°37′39.1″D). Su örnekleri steril falcon tüplerine alınarak soğuk zincir altında laboratuvara taşınmıştır.

50 mL su örnekleri, %0,85 NaCl ile seri olarak (1:10) seyreltilmiştir. Her bir seyreltiden 200 µL süspansiyon yayma plak tekniği kullanılarak Nutrient Agara (NA) transfer edilmiş ve 30 °C'de 96 saat inkübe edilmiştir. Ardından besiyerinde büyüyen koloniler seçilerek tek tek NA'ya aktarılmıştır. İzolatların alt kültürleri yapılmış ve daha sonraki çalışmalar için -80 °C'de gliserollü stokları hazırlanmıştır.

2.2. Bakteri İzolatının Tanımlanması

Seçilen izolatların moleküler tanımlaması, 16S rRNA gen bölgelerinin DNA dizi analizi ve aynı bölgeye karşılık gelen proteinler için matris destekli lazer desorpsiyon/iyonizasyon uçuş zamanı kütle spektrometrisi (MALDI-TOF) ile gerçekleştirilmiştir (Akdeniz Üniversitesi Hastanesi Merkez Laboratuvarı, Antalya). İzolatların genomik DNA izolasyonu, ticari bir genomik DNA izolasyon kiti kullanılarak yapılmıştır (Zymo Research, ABD). 16S rRNA gen bölgesinin PCR amplifikasyonu için evrensel primerler (8F ve 1492R) kullanılmış ve reaksiyonlar önceden belirlenmiş bir protokole göre gerçekleştirilmiştir (Eden ve ark., 1991). PCR ürünleri, daha önce tanımlandığı şekilde iki yönlü olarak Sanger dizilemesi ile analiz edilmiştir (Delik ve ark., 2024). Sonuçlar, National Center for Biotechnology Information (NCBI) veritabanının Temel Yerel Hizalama Arama Aracı (BLASTn) programı kullanılarak hizalanmış ve izolatlar moleküler olarak tanımlanarak NCBI erişim numaraları elde edilmiştir.

2.3. Antibiyotik Duyarlılığı ve MİK Değerlerinin Belirlenmesi

Bakteri izolatının antimikrobiyal duyarlılığının belirlenmesi için Clinical and Laboratory Standards Institute (CLSI) tarafından tanımlanan disk difüzyon yöntemi kullanılmıştır (CLSI, 2021). Çalışmada kullanılan antibiyotik diskleri (Biyoanaliz, Türkiye); antimetabolitlerden trimetoprim-sülfametoksazol (TMP-SMX) (1,25/23. 75 µg/disk), beta laktamlardan ampisilin (10 µg/disk), imipenem (10 µg/disk), meropenem (10 µg/disk), sefazolin (30 µg/disk), seftazidim (30 µg/disk), seftriakson (30 µg/disk) ve sefuroksim (30 µg/disk), kloramfenikol antibiyotik grubundan kloramfenikol (30 µg/disk), makrolidlerden azitromisin (15 µg/disk), klaritromisin (15 µg/disk) ve eritromisin (15 µg/disk), kinolonlardan siprofloksasin (5 µg/disk) ve tetrasiklin antibiyotik grubundan tetrasiklin (30 µg/disk) kullanılmıştır. Bakteri hücreleri CLSI standartlarına uygun olarak %0.85'lik NaCI içerisinde 0.5 McFarland standartına ayarlanmış ve Mueller Hinton Agar (MHA) besiyerine yayılmıştır. Antibiyotik diskleri bakteri ekimi gerçekleştirilmiş MHA üzerine yerleştirilmiştir. Hazırlanan örnekler 37 °C'de 24 saat inkübe edilmiştir. İnkübasyonun ardından antibiyotiklerin oluşturduğu zon çapları ölçülmüş ve antimikrobiyal duyarlılık profili (dirençli veya duyarlı) CLSI standartlarına göre belirlenmiştir.

Antibiyotiklerin MİK değerlerini belirlemek için sıvı dilüsyon yöntemi kullanılmıştır (CLSI, 2021). Farklı konsantrasyonlarda antibiyotik içeren Mueller Hinton Broth'a (MHB) 0.5 McFarland standardına ayarlanmış bakteri hücreleri eklenmiştir. Örnekler 37 °C'de 150 rpm'de 24 saat boyunca inkübe edilmiştir. İnkübasyon sonunda, bakteri üremesinin olmadığı en düşük antibiyotik konsantrasyonu MİK olarak belirlenmiştir.

2.4. Sub-MİK'lerin Biyofilm Oluşumuna Olan Etkilerinin Belirlenmesi

Antibiyotiklerin biyofilm oluşumuna olan etkileri, Tang ve ark., (2020)'nın belirtiği yönteme göre modifiye edilerek belirlenmiştir. Bakteri hücrelerinin başlangıç konsantrasyonu Nutrient Broth (NB) besiyerinde OD600 nm'de 0.05 absorbans değerine ayarlanmış ve örnekler üzerine son konsantrasyon MİK/2 ve MİK/4 olacak şekilde antibiyotik ara stoklarından eklenmiştir. Hazırlanan örneklerden 96 kuyucuklu hücre kültürü plakasının her bir kuyucuğuna 200 µL eklenmiştir ve 37 °C'de 24 saat statik koşullarda inkübe edilmiştir. İnkübasyonun ardından plakalarda yer alan örnekler dökülmüş ve plakaların her bir kuyusu distile su ile yıkanmıştır. Yıkama adımının ardından oluşan biyofilmler 200 µL kristal viyole çözeltisi (%0,1) ile 30 dakika boyanmıştır. Ardından fazla boya distile su yardımıyla uzaklaştırılmış ve kalan biyofilmler %95 etanol ile çözdürülerek OD590'da absorbans değerleri alınmıştır.

2.5. Sub-MİK'lerin Bakteri Morfolojisi Üzerindeki Etkilerinin Belirlenmesi

Bakteri morfolojisindeki değişiklikler ışık mikroskobu kullanılarak incelenmiştir. Bakteri izolatı son konsantrasyon MİK/2 ve MİK/4 olacak şekilde antibiyotik içeren NB'de 37 °C'de 150 rpm'de 24 saat inkübe edilmiştir. İnkübasyonun ardından, her kültürden örnek alınarak lam üzerine sabitlenmiş ve Gram boyamaları yapılmıştır. Sub-MİK antibiyotiklerin bakteri morfolojisi üzerindeki etkisi, boyanmış örneklerin mikroskop altında incelenmesiyle belirlenmiştir.

2.6. İstatistik Analizler

Tüm deneyler birbirinden bağımsız olarak en az 3 tekrarlı olarak gerçekleştirilmiştir. İstatistiksel analizler tek yönlü varyans analizi (ANOVA) (IBM SPSS yazılım programı sürüm 22) (SPSS, ABD) kullanılarak gerçekleştirilmiştir. Ayrıca, çoklu karşılaştırmalarda farklılıkların hangi gruplar arasında olduğunu belirlemek için tamamlayıcı bir Post-Hoc analizi olarak Tukey testi kullanılmıştır. $P<0.05$ olan örnekler istatistiksel olarak anlamlı kabul edilmiştir.

3. Bulgular

3.1. Bakteri İzolatının Tanımlanması

Antalya'daki tatlı su kaynağından izole edilen bakteri kolonisi hem 16S rRNA gen bölgesinin DNA dizi analizi hem de MALDI-TOF ile tanımlanmıştır. Her iki analizde de bakteri izolatı *A. veronii* by *veronii* NAA12 (GenBank ID: PQ219646.1) olarak tanımlanmıştır.

3.2. Antibiyotik Duyarlılığı ve MİK Değerleri

Bakterinin antimikrobiyal duyarlılığı ve duyarlı olduğu antibiyotikler için MİK değerleri Tablo 1'de verilmiştir. İzolatın ampisilin, seftazidim, seftriakson ve TMP-SMX antibiyotiklerine karşı dirençli olduğu gözlemlenmiştir.

Antibiyotiklerin MİK değerleri karşılaştırıldığında, en yüksek MİK değerinin azitromisin antibiyotiğine ait olduğu belirlenmiştir. En düşük MİK değerleri ise beta-laktam üyesi olan karbapenem grubu antibiyotiklere (imipenem ve meropenem) karşı gözlemlenmiştir.

Tablo 1. Bakterinin antibiyotik duyarlılığı ve MİK değerleri

Antibiyotikler	Antibiyotik Duyarlılığı	MİK (µg/mL)
TMP-SMX	R	-
Ampisilin	R	-
İmipenem	S	0.01
Meropenem	S	0.03
Sefazolin	S	0.06
Seftazidim	R	-
Seftriakson	R	-
Sefuroksim	S	4
Kloramfenikol	S	4
Azitromisin	S	6
Klaritromisin	S	0.5
Eritromisin	S	1
Siprofloksasin	S	0.07
Tetrasiklin	S	0.3

R= dirençli, S= duyarlı

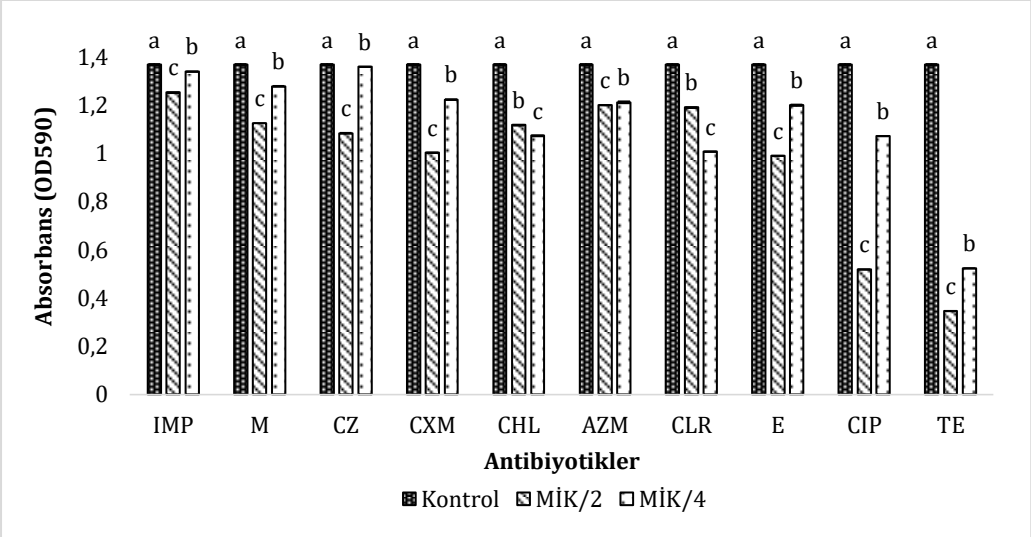
3.3. Sub-MİK'lerin Biyofilm Oluşumuna Olan Etkileri

Tüm antibiyotiklerin MİK/2 ve MİK/4 dozları antibiyotiksiz ortamda yetiştirilen bakteriye kıyasla biyofilm oluşumunu azaltmıştır ($P<0.05$) (Şekil 1). Biyofilm oluşumuna karşı en etkili antibiyotiğin tetrasiklin olduğu görülmüştür. MİK/4 sefazolin ve imipenem varlığında biyofilm miktarının kontrole yakın olduğu gözlemlenmiştir. Ayrıca, sub-MİK kloramfenikol ve klaritromisin varlığında oluşan biyofilm miktarları karşılaştırıldığı zaman antibiyotiklerin MİK/2 dozlarındaki biyofilm oluşumunun MİK/4 dozlarına göre istatistiksel olarak daha yüksek olduğu tespit edilmiştir.

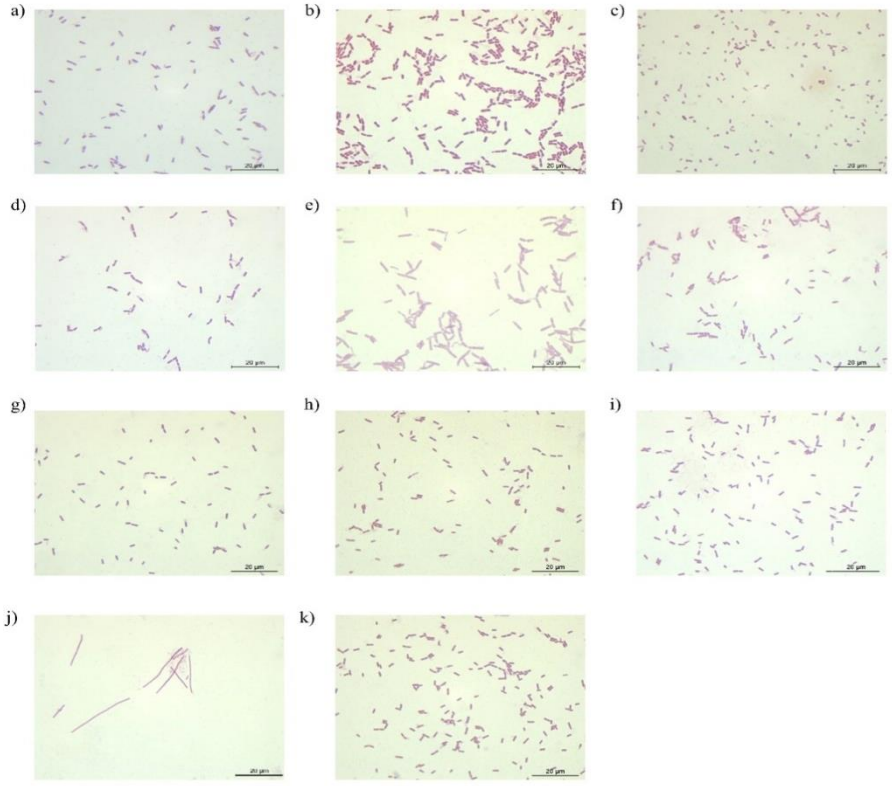
3.4. Sub-MİK'lerin Bakteri Morfolojisi Üzerindeki Etkileri

Sub-MİK antibiyotik varlığında büyütülen bakterilerde meydana gelen morfolojik değişiklikler Şekil 2'de gösterilmiştir. MİK/2 ve MİK/4 antibiyotik varlığında büyütülen bakteri hücrelerinin hücre morfolojilerinin

benzer olduğu gözlemlenmiştir. Bakteriyel morfolojideki en belirgin değişiklik siprofloksasin ve meropenem antibiyotiklerinde gözlemlenmiştir. Antibiyotik uygulamasından önce basil hücre morfolojisine sahip bakteri hücreleri meropenem uygulamasının ardından yuvarlak bir morfoloji gösterirken siprofloksasinli ortamda büyütülen bakteri hücreleri inkübasyon sonunda uzun filament yapıda bir hücre morfolojisi sergilemiştir. Ayrıca sefuroksim varlığında bakteri hücreleri kontrol grubuna kıyasla daha uzun bir hücre morfolojisi sergilemiştir. Ancak bu değişim, siprofloksasin ve meropenem sub-MİK'lerindeki değişim kadar net olmamıştır. Çalışmada kullanılan diğer antibiyotikler ise bakteri hücrelerinde morfolojik değişime neden olmamıştır.



Şekil 1. Sub-MİK'lerin biyofilm oluşumuna etkisi. Kontrol= antibiyotiksiz ortamda büyütülmüş bakteri, IMP= imipenem, M= meropenem, CZ= sefazolin, CXM= sefuroksim, CHL= kloramfenikol, AZM= azitromisin, CLR= klaritromisin, E= eritromisin, CIP= siprofloksasin, TE= tetrasiklin. Üst simgelerde yer alan farklı harfler istatistiksel olarak anlamlı farklılığı göstermektedir ($P<0.05$).



Şekil 2. Sub-MİK'lerin bakteri morfolojisine etkisi, a) Kontrol (antibiyotiksiz ortamda büyütülmüş bakteri), b) imipenem c) meropenem d) sefazolin e) sefuroksim f) kloramfenikol g) azitromisin h) klaritromisin i) eritromisin j) siprofloksasin k) tetrasiklin.

4. Tartışma

Bu çalışma Antalya'daki tatlı su kaynağından izole edilen *A. veronii* izolatının antimikrobiyal duyarlılığını ve sub-MİK antibiyotiklerin biyofilm oluşumu ve morfolojik değişiklikler üzerindeki etkilerini araştırmıştır. Bulgularımız, çevresel *Aeromonas* türlerinin antibiyotiklere karşı direnç geliştirme potansiyelini ortaya koyarak, bu bakterilerin hem insan sağlığı hem de çevresel riskler açısından önemini vurgulamaktadır. *Aeromonas* türlerinin çevresel adaptasyon kabiliyeti onları birçok farklı ortamda hayatta kalmaya uygun hale getirmektedir (Pessoa ve ark., 2019). Çeşitli çalışmalarda, bu bakterilerin gıda ürünlerinde, su kaynaklarında ve insan enfeksiyonlarında yaygın olarak bulunduğu ve izole edildiği görülmüştür (Li ve ark., 2015; Alhazmi, 2015).

Bu çalışmanın bulguları izolatın TMP-SMX, ampisilin, seftazidim ve seftriakson gibi yaygın antibiyotiklere dirençli olduğunu ve bu durumun çevresel *Aeromonas* türlerinin halk sağlığı açısından ciddi bir risk oluşturabileceğini göstermektedir (Janda ve Abbott, 2010). Özellikle *Aeromonas* cinsinin sucul ortamlarda yaygın olması ve antropojenik etkiler nedeniyle bu ortamlarda antibiyotik dirençli suşların gelişme olasılığının yüksek olması, bu bakterilerin izlenmesi gerektiğini ortaya koymaktadır (Gomes ve ark., 2021). Benzer şekilde Eid ve ark., (2022) tarafından yapılan bir çalışmada, Akdeniz'den izole edilen *Aeromonas* suşlarının %90'ının çoklu ilaca dirençli olduğu bildirilmiştir. Ayrıca Woo ve ark., (2022), Kore'de su hayvanlarından izole edilen *A. veronii* ve *A. hydrophila* suşları arasında çoklu ilaca dirençli suşlar bulunduğunu ve bu suşlarda direnç genlerinin yaygın olduğunu bildirmiştir. Bu durum, çevresel kaynaklı *Aeromonas* türlerinin insan sağlığı için potansiyel bir tehdit oluşturabileceğini göstermektedir.

Biyofilm oluşumu *Aeromonas* türlerinin önemli bir virülans faktörüdür ve bu bakterilerin çeşitli yüzeylere tutunarak enfeksiyona yol açma potansiyelini artırır (Dias ve ark., 2018). Bu çalışmada sub-MİK'lerin *A. veronii* izolatının biyofilm oluşumunu önemli ölçüde azalttığı görülmüştür. Bu bulgu antibiyotiklerin düşük konsantrasyonlarının bile biyofilm oluşumu üzerinde önemli etkileri olabileceğini göstermektedir (Lebeaux ve ark., 2014). Ancak Dias ve ark. (2018) yaptıkları çalışmada, yüksek konsantrasyonlardaki antibiyotiklerin biyofilm oluşumunu etkileyemediğini belirtmişlerdir. Bu çelişkili bulgular, biyofilm oluşumunun antibiyotik türü ve konsantrasyonuna bağlı olarak değişkenlik gösterebileceğini düşündürmektedir. Biyofilm oluşumuna karşı en etkili antibiyotiğin tetrasiklin olduğu bulgumuz, bu ilacın biyofilmle ilişkili enfeksiyonların tedavisinde potansiyel olarak kullanılabileceğini göstermektedir. Ancak antibiyotiklerin sub-MİK konsantrasyonlarının biyofilm oluşumunu farklı şekilde etkileyebileceği bulgusu, biyofilm oluşumunun antibiyotik konsantrasyonlarına duyarlı olduğunu göstermektedir (Lebeaux ve ark., 2014). Özellikle kloramfenikol ve klaritromisin gibi antibiyotiklerin daha düşük konsantrasyonlarda biyofilm oluşumunu fazla etkilememiş olması bu tür alt-doz uygulamaların direnç gelişimi ve enfeksiyon kontrolünde dikkate alınması gerektiğini göstermektedir.

Morfolojik değişiklikler açısından sub-MİK siprofloksasin ve meropenem varlığında *A. veronii* izolatında gözlemlenen belirgin değişiklikler, bu antibiyotiklerin hücre bölünmesini ve morfolojiyi etkileyebileceğini göstermektedir (Lewis, 2001). Bu tür morfolojik değişiklikler bakterilerin çevresel stres faktörlerine adaptasyon mekanizmaları ile ilişkili olabilir ve bakterilerin hayatta kalma stratejilerini anlamak için önemlidir. Salama (2020)'nin belirttiğine göre bakteri morfolojisi de bir virülans belirleyicisidir ve bakteri direncinde rol oynayan faktörlerden biridir. Örneğin kıvrımlı morfoloji yüzeye tutunma ve kolonizasyonda, çubuk şeklindeki morfolojinin ise yüzey tutunmasında, komşu hücrelerle iletişimde ve biyofilm oluşumunda daha etkili olduğu belirtilmiştir (Persat ve ark. 2014; Lin ve ark. 2015). Bu nedenle *A. veronii* izolatında meydana gelen bu morfolojik değişikliklerin antibiyotik direnç mekanizmaları ile bağlantılı olabileceği düşünülmektedir (Rowlett ve ark., 2017).

Sub-MİK antibiyotiklerin bakteri morfolojisi ve biyofilm oluşumu üzerindeki etkilerinin anlaşılması antibiyotik direnç mekanizmalarının karmaşıklığını çözmek için önemlidir. Sub-MİK seviyelerinin, bakterilerin çevresel stres faktörlerine adaptasyonunu ve virülansını nasıl etkilediğini incelemek hem çevresel hem de klinik açıdan önemli bulgular sunabilir. Bu nedenle, antibiyotiklerin yalnızca terapötik dozlarının değil, aynı zamanda düşük konsantrasyonlarının da bakteri davranışı üzerindeki etkilerini araştırmak, antibiyotik direncinin yayılmasını önlemek ve etkili tedavi stratejileri geliştirmek için önemlidir. Bu bulgular, antibiyotiklerin sub-MİK dozlarının potansiyel risklerini daha iyi anlamamız gerektiğini ve bu konuda daha fazla araştırma yapılmasının gerekliliğini vurgulamaktadır.

4. Sonuç

Bu çalışma *Aeromonas* türlerinin çevresel ve klinik ortamlarda antibiyotik direnci ve biyofilm oluşturma potansiyelini vurgulamakta ve bu bakterilerin izlenmesi ve kontrol edilmesi gerektiğini ortaya koymaktadır. Antibiyotiklerin düşük konsantrasyonlarının bile bakteriyel özellikler üzerinde önemli etkileri olabileceği gerçeği, çevresel antibiyotik kirliliğinin kontrol altına alınması gerektiğini vurgulamaktadır. Gelecekte yapılacak çalışmalar, bu bakterilerin direnç mekanizmalarını ve çevresel yayılımlarını daha iyi anlamaya yönelik olmalıdır.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	B.E.	E.D.	B.E.T.Ö.
K	34	34	33
T	34	34	33
Y	30	30	40
VTI	34	34	33
VAY	34	34	33
KT	34	34	33
YZ	34	34	33
KI	30	30	40
GR	34	34	33
PY	30	30	40
FA			100

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

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MEKANİSTİK-AMPİRİK TASARIM YAKLAŞIMIYLA SİLİNDİRLE SIKIŞTIRILMIŞ BETON YOL PERFORMANS DEĞERLENDİRMESİ: ANKARA TEMELLİ YOLU ÖRNEĞİ

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Özet: Sağladığı uzun dönemli ekonomik kazançlar ve hızlı trafiğe açılması gibi avantajları sayesinde Silindirle Sıkıştırılmış Beton (SSB) yol teknolojisi, ülkemizde belediye uygulamaları da dahil edildiğinde 5.000 km'yi aştığı tahmin edilmektedir. Ancak halen çoğunlukla geleneksel katalog sistemi ile tasarımlar yapılmakta ve çevresel koşullar, iklim, zemin, malzeme ve trafik koşulları yeterince dikkate alınmamaktadır. Bunun sonucunda da bazı uygulamalarda uzun dönemli öngörülemeyen performans düşüşleri yaşanabilmektedir. Bu çalışma ile Amerika Birleşik Devletleri ve Kanada'nın öncülüğünde, kullanımı her geçen gün artan yeni nesil mekanistik-ampirik (M-E) üstyapı yaklaşımı ile Ankara ili Polatlı ilçesine bağlı Temelli mevki Çokören- Babayakup köyleri arasında SSB Yolu tekrardan tasarlanmış ve gerçek saha SSB yol performansı ile program modellemesi tahminleri karşılaştırılmıştır. Sonuç, M-E yaklaşımının geleneksel tasarım yöntemlerine göre daha gerçekçi tahmin yapabildiği yönündedir. Bu tasarım yöntemi, bu uygulama özelinde derz bırakılmaması ve ince kalınlık tasarımı yapılması gibi tasarımsal kararların uzun dönemli üstyapı performansını nasıl etkilediğini göstermiş ve servis süresi boyunca daha etkin ve daha ekonomik (uzun dönemli) tasarımlar optimize etmiştir. Bu çalışmanın nihai amacı ise SSB yol uygulamaları için ülkemiz özelinde yerel malzeme ve iklim koşulların dahil edildiği ve mevcut SSB yol uygulamaları ile kalibre edilecek bir M-E esaslı üstyapı tasarım programının hayata geçirilmesine öncülük etmesidir.

Anahtar kelimeler: Silindirle Sıkıştırılmış Beton (SSB) kaplama, Üstyapı tasarımı, Mekanistik-ampirik üstyapı tasarımı

Performance Assessment of the Roller Compacted Concrete Pavement with Mechanistic-Empirical Design Approach: A Case Study of Ankara Temelli Road

Abstract: Due to its long-term economic benefits and rapid opening to traffic, Roller Compacted Concrete (RCC) pavement technology has been widely implemented across Türkiye, with applications exceeding 5,000 km, including municipal projects. However, designs are predominantly based on traditional catalog systems, often neglecting critical factors such as environmental conditions, climate, soil, materials, and traffic loadings. Consequently, some applications experience unforeseen long-term performance issues. In this study, the RCC road design between Çokören and Babayakup villages in the Temelli district of Polatlı, Ankara, was evaluated using the mechanistic-empirical (M-E) pavement approach, which has been pioneered and increasingly adopted by the USA and Canada. The actual field performance of the RCC road was compared with predictions from the M-E modeling. The findings indicate that the M-E approach provides significantly more realistic predictions compared to traditional design methods. This approach demonstrated how specific design decisions, such as omitting joints and opting for thinner pavement thicknesses, impact long-term pavement performance, thereby optimizing more efficient and economical (long-term) designs throughout the service life. The ultimate goal of this study is to pave the way for the development of an M-E-based pavement design program tailored to Türkiye's local materials and climate conditions, calibrated with existing RCC road applications.

Keywords: Roller Compacted Concrete (RCC) pavement, Pavement design, Mechanistic-empirical design approach

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1. Giriş

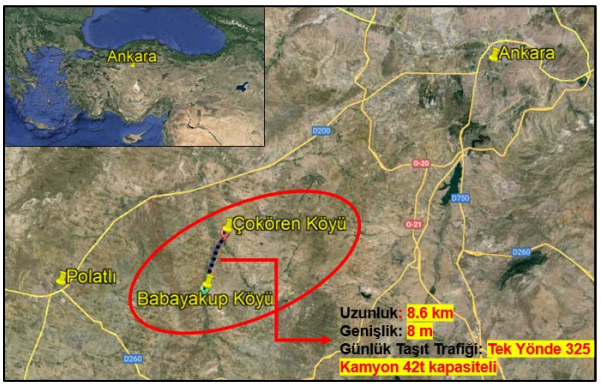
Özel bir rijit kaplama türü olan Silindirle Sıkıştırılmış Beton (SSB) yol teknolojisi, isminden de anlaşılacağı üzere kuru katı kıvamı ile taze halde iken ağır vibrasyonlu çelik tambur ve lastik tekerlekli silindirleri taşıyarak betonun sıkıştırılmasına ve son şeklinin verilmesine olanak sağlamaktadır. Bu özel beton yol teknolojisi sıkıştırma ve serim yöntemi ile geleneksel esnek (asfalt) yollara benzerlik gösterirken, sahip olduğu aynı malzeme içeriğinden (çimento, su ve ince ve kaba agregalar) dolayı bir beton yol türü olarak sayılmaktadır (Harrington ve ark., 2010). Bu hibrid beton yol teknolojisi geleneksel asfalt ve beton yolların avantajlarını bir arada tutmasından dolayı her geçen gün kullanımı artmaktadır. Asfalt yollara benzer biçimde sahip olduğu kuru katı kıvamıyla herhangi bir kalıp vb.

ekipmana ihtiyaç duyulmadan serilip sıkıştırılarak hızlı bir şekilde trafiğe açılabilmesinin yanı sıra geleneksel beton yol gibi uzun ömürlü ve ağır tonajlı tekrarlı trafik yüklerine karşı dayanıklı olması en önemli avantajları arasında sayılmaktadır. Asfalt kaplama malzemesine kıyasıyla çimento, su ve agregalardan oluşan malzeme içeriğiyle, ham madde arzında konjektürel gelişmelerden az etkilenmesi ve ayrıca geleneksel beton yollardan da daha az çimento ve suya ihtiyaç duyması da sürdürebilirlik ve ekonomik açısından bir avantaj teşkil etmektedir (Akbelen ve ark., 2023). Bununla birlikte daha iyi sıkıştırılması ve sıkı bir matrisin elde edilmesi için daha fazla ince agrega kombinasyonuna ihtiyaç duymaktadır. Bu zamana kadar SSB tasarım karışımı ve oranlamalarının, SSB mekanik performansına etkileri üzerine oldukça fazla çalışma yapılmıştır. Diğer taraftan SSB yol teknolojisinde daha fazla üzerinde durulması ve araştırılması gereken bazı başlıklar bulunmaktadır. Bunların başında uzun dönemli yapısal ve durabilite performanslarının tahmini gelmektedir. Ayrıca gerek malzeme karışım tasarımlarında gerekse kalınlık yapısal tasarımlarında halihazırda kullanılan yaklaşımların çoğunlukla geleneksel yöntem ve metotlara bağlı olarak korumacı kalması, bu alanların da araştırmacılar tarafından tekrar irdelenmesini gerektirmektedir (Abdo, 2023).

İlk olarak, 1970'li yıllarının başında yapılan başarılı uygulamalar ile Kanada ve Amerika Birleşik Devletleri'nde SSB yol teknolojisinin tanınırlığı başlamış olsa da sağlamış olduğu avantajların yanı sıra gelişen yüksek sıkıştırma teknolojisine sahip sericilerin de piyasada yer almaya başlaması ile son yıllarda popülerliği daha da artmıştır.

Ülkemizde ise ilk SSB yol uygulamaları Antalya (2009), Denizli (2011), Samsun (2014) ve Tekirdağ (2016) Büyükşehir Belediyeleri ile il özel idarilerinin girişimleri ile başlamış ve 2023 yılı sonu itibariyle ülkemizde SSB yol uygulaması 55 farklı ilde 5.000 km'yi geçmiştir. Bu sayılarla dünya genelinde geniş ölçekli SSB yol uygulamalarının gerçekleştirildiği birkaç ülkeden biri konumuna gelmemize rağmen, mevcut uygulamalarda SSB yapısal tasarımlarının halen geleneksel yöntemlerle (katalog tasarımı) yapıldığı ve çoğu zaman yerel zemin, iklim ve uzun dönemli trafik koşullarının yeterince dikkate alınmadan benzer kalınlıkların kullanıldığı görülmektedir.

Bu çalışmada lokasyon bilgilerinin Şekil 1'de görüldüğü, Ankara Büyükşehir Belediyesi yol ağında bulunan Ankara ili Polatlı ilçesine bağlı Temelli mevki Çokören-Babayakup köyleri arasında yaklaşık 8,6 km'lik SSB Yol uygulaması ele alınmıştır. 2018 yılında inşa edilen SSB Yol iki şeritli olarak 8 m genişlikle inşa edilmiş ve yapısal kalınlık tasarımı geleneksel yöntemlerle yapılmıştır.



Şekil 1 Ankara Temelli SSB Yol uygulamasına ait lokasyon.

Bu çalışmanın amacı, geleneksel yöntemlerle yapısal kalınlık tasarımı yapılan bu SSB Yol uygulamasının son yıllarda ABD ve Kanada'da popülerliği artan yeni nesil mekanistik-ampirik (M-E) üstyapı tasarım yaklaşımı ile yeniden tasarlanıp uzun dönemli performans tahminlerinin yapılmasıdır. Bu amaçla, ilk olarak mevcut yola ait tasarım bilgileri derlenerek, ABD'de geliştirilen M-E üstyapı rehberinin (AASHTO, 2015) esas alındığı AASHTOWare Pavement M-E Design Software (PMED) Ver. 2.6 sonlu elemanlar programı ile tekrar analizi yapılmış ve otuz yıllık servis süresi boyunca çatlak, faylanma ve yüzey düzgünsüzlüğü açısından performans tahminleri hesaplanmıştır. Bu tahminlerin saha ölçümleri ile ne derecede eşleştiğinin gözlemlenebilmesi adına, gerçek saha performanslarıyla karşılaştırılmalar yapılmıştır. Ayrıca Temelli SSB yolunun servis süresi boyunca yeterli performansı göstermesi için tasarım parametrelerin optimizasyonu da bu çalışma kapsamında yapılmış ve böylece, optimum üstyapı yapısal tasarımı ortaya konulmuştur. Bu çalışmanın bir diğer önemli amacı ise SSB Yol uygulamalarında öncü ülkelerinden biri konumundaki ülkemize ait bir tasarım metodolojisinin geliştirilmesine ve bunu takip edecek yerel kalibrasyon çalışmalarına öncülük etmesidir.

2. Materyal ve Yöntem

Bu çalışma kapsamında ilk olarak Ankara Polatlı ilçesine bağlı Temelli mevki Çokören- Babayakup köyleri arasında 8,6 km'lik SSB yol uygulamasına ait tasarım parametreleri Türkçimento ve yüklenici firma yetkililerinden alınarak Tablo 1'de derlenmiştir. 120m^3/saat kapasite ile üretilen beton, tandem çalışan 2 finişer (serici) ile eş zamanlı olarak yola serilmiştir. Sıkıştırma işlemi için çelik tamburlu ve lastik tekerlekli silindirler kullanılmıştır. SSB yol inşa aşamasına ait görseller Şekil 2'de görülmektedir. Kür uygulaması sırasında TS 10966 standardına göre 0,35 lt/m^2'lik kimyasal kür uygulaması gerçekleştirilmiştir. Bu SSB yol uygulaması sırasında derz bırakılmamıştır.

Tablo 1. Mevcut Temelli SSB yol uygulamasına ait tasarım parametreleri

SSB Yol Uygulaması Geometrik Tasarım Parametreleri
Yol lokasyonu: Çokören- Babayakup köyleri arası kırsal yol Yol uzunluğu: 8600 m Yol genişliği: 8 m
SSB Yol Uygulaması Trafik Tasarım Parametreleri
Trafik: Tek yönde 325 adet 42 ton yüklü kamyon trafiği
SSB Yol Kesiti
SSB kaplama: 17 cm Plentmiks Temel (PTM): 20 cm Derz uygulaması: Yok
SSB malzeme karışım oranlaması
Çimento: 350 kg/m^3 Su: 109 kg/m^3 Toplam Agrega: 2025 kg/m^3 Yoğunluk: 2484 kg/m^3

Kalite kontrol testleri kapsamında, sahada TS 1900-1 standardına göre kum konisi testi–uygulanmasının yanı sıra ASTM D6938 standardı da takip edilerek nükleer metot yöntemi ile sıkıştırma kontrolleri gerçekleştirilmiştir. Ayrıca sahadan alınan beton örnekleri ASTM C1435 standardına göre titreşimli tokmak ile küp numuneler halinde sıkıştırılmıştır. TS EN 12390-3'e göre laboratuvarda 28 günlük hedef dayanım sınıfı olan C30/37 üzeri dayanımlar elde edilerek kalite kontrol testleri gerçekleştirilmiştir. SSB yol 24 saat içinde mastar ile düzgünsüzlük kontrollü sonrası trafiğe açılmıştır.

Şekil 2. Temelli SSB yol inşasına ait fotoğraflar.

SSB yol uygulamasına ait tasarım parametrelerinin derlenmesinin ardından geleneksel yaklaşımlarla belirlenen kalınlıkların halihazırdaki iklim ve zemin koşulları altında ne derecede performans gösterebileceğinin belirlenmesi için AASHTOWare PMED sonlu eleman programı ile tekrar analizi yapılmıştır. Otuz yıllık servis süresi boyunca çatlak, faylanma ve yüzey düzgünsüzlüğü açısından performans tahminleri hesaplanması Bölüm 3'te ele alınarak performans tahminlerinin saha ölçümleri ile ne derece eşleştiğinin gözlemlenebilmesi adına gerçek saha performanslarıyla karşılaştırılmalar yapılmıştır.

3. Bulgular

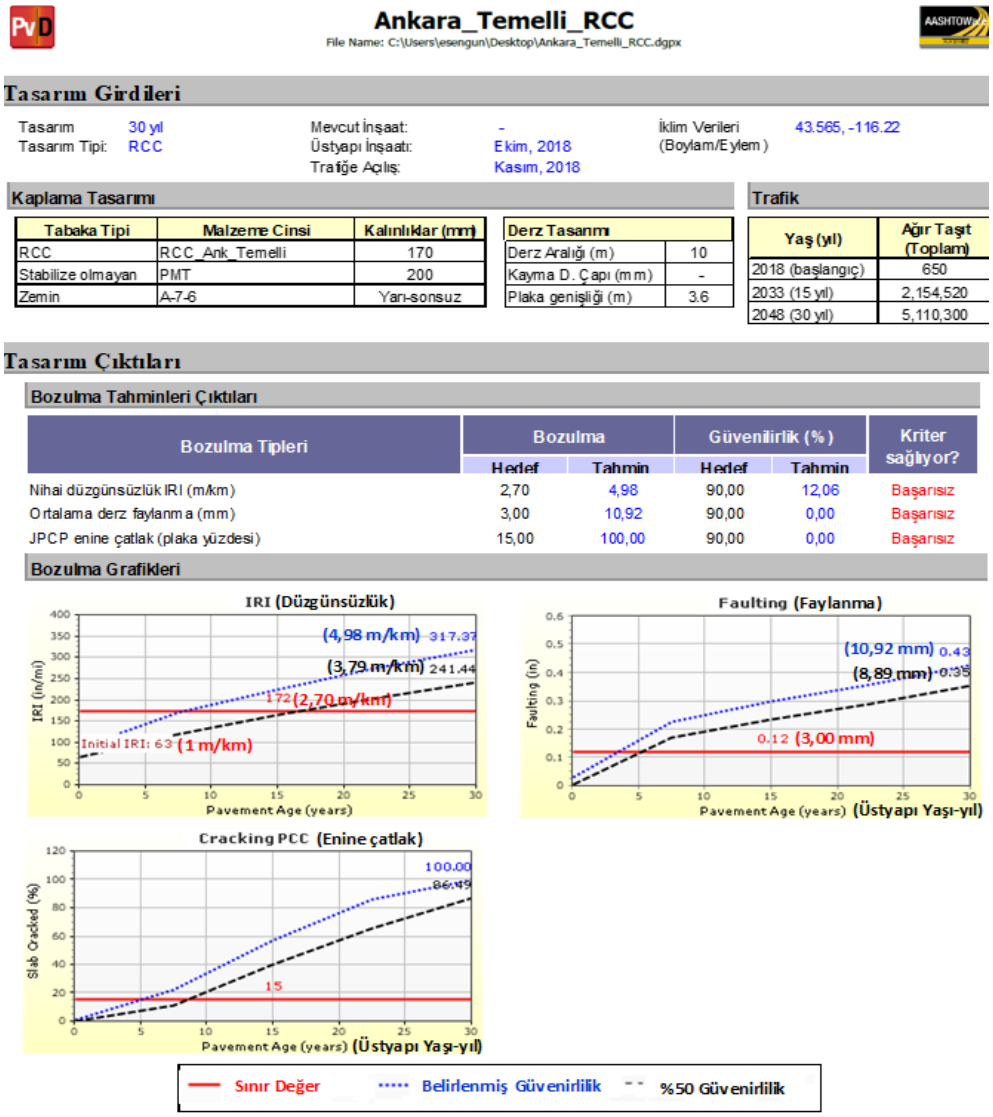
3.1. M-E Yaklaşımla Performans Analizleri ve Gerçek Saha Performansı

Yeni nesil M-E üstyapı tasarım rehberi, geleneksel yöntemlerinin malzeme, trafik yükü ve iklim gibi parametrelerin doğrudan kullanılmaması gibi kısıtlamaları içermesinden dolayı, yol üstyapılarının daha gerçekçi olarak tasarlanabilmesi adına ilk olarak ABD ve Kanada'da geliştirilmiş ve zamanla diğer ülkeler tarafından kullanılmaya başlamıştır (Islam ve ark., 2023; Öztürk ve ark., 2019). Bu yeni nesil üstyapı M-E tasarım yaklaşımının mekanik kısmını (M) trafik yüklerine ve çevresel koşullara bağlı olarak üstyapıda meydana gelecek gerilme, birim şekil değiştirme ve deformasyon hesaplamaları oluştururken, bu mekanik büyüklüklerin güvenilirlik katsayıları da göz önüne alınarak ampirik bozulma transfer fonksiyonlarına bağlı olarak çatlak, faylanma ve düzgünsüzlük gibi üstyapı performansını etkileyen parametrelere dönüştürülmesi ve zamana göre tahmin edilebilmesi de tasarımın ampirik kısmını (E) oluşturmaktadır. Bundan dolayı tasarımın ampirik kısmını oluşturan üstyapıda meydana gelecek bozulmaların tahmin edilebilmesi için mevcut daha önceki üstyapı tecrübe ve gözlemlerine de dayanarak programın yerel kalibrasyonun yapılması, tasarımın daha gerçekçi sonuç vermesi ve bozulma tahminlerinin daha doğru yapabilmesi adına oldukça önemlidir (Sengun ve ark., 2020). Her ne kadar M-E üstyapı rehberinin (AASHTO, 2015) esas alındığı AASHTOWare PMED sonlu eleman programı bu özel beton yol türü olan SSB'ler için özelleştirilmediğinden dolayı dersiz, donatısız geleneksel beton yol gibi tasarlansa da yine de SSB tasarımında bu programın kullanımı Federal Amerikan Karayolları Birliği (FHWA) tarafından önerilmektedir (FHWA-HIF-16-003, 2016). Sengun (2024) tarafından yapılan çalışmada ise mevcut ABD'deki SSB yolların AASHTOWare PMED sonlu elemanlar programıyla yeniden analizi yapıldığında, hesaplanan performans tahminlerinin bir dereceye kadar gerçek saha tahminleri ile örtüştüğü görülmüştür (Sengun, 2024).

Çalışmanın ilk aşamasında, Temelli mevki Çokören-Babayakup köyleri arasındaki geleneksel yöntemlerle (katalog) tasarımı yapılan mevcut SSB yolu, M-E esaslı AASHTOWare PMED programı ile yeniden tasarlanarak servis süresi boyunca çatlak, faylanma ve yüzey düzgünsüzlüğü açısından performans tahminleri hesaplanmıştır. Bunun için ilk olarak güzergâha ait iklim verilerinin programa tanıtılması gerekmektedir. Ancak programda sadece ABD ve Kanada hava istasyonlarına ait iklim verileri girdilerine izin vermesinden dolayı, güzergâh iklimi; yıllık ortalama hava sıcaklığı, yıllık ortalama yağış miktarı, don indeksi ve yıllık ortalama

donma/çözülme döngüsü sayısı esas alınarak ABD'deki en yakın hava istasyonu ile eşleştirilmiştir. Buna göre güzergâh iklimi verileri ile ABD Idaho City'e ait Boise Airport Hava İstasyonu iklim verileri önemli benzerlikler gösterdiği için modellemede bu iklim verileri kullanılarak devam edilmiştir.

Şekil 3'ten de görüldüğü üzere modelleme sonucu mevcut SSB yolunun servis ömründen daha önce çatlak, faylanma ve yüzey düzgünsüzlüğü açısından sınır değerleri aşacağı tahmin edilmektedir. Özellikle çatlak performansı açısından modelleme, SSB inşaatının beş ile on yıl arasında sınır değerleri aşacağını göstermektedir. Bunun en önemli sebebi ise inşa edildiği yıllarda yaygın bir uygulama olan SSB yol inşaatı sırasında derz uygulamasının yapılmamasıdır. Ancak son yıllarda gerek ABD'de gerekse ülkemizde derz bırakılmasının çatlak kontrolü ve yol üstyapı performansı acısından daha olumlu sonuçlar doğurduğu görülerek, bu uygulamalardan çoğunlukla vazgeçilmiştir. Burada belirtilmesi gereken önemli bir nokta AASHTOWare PMED sonlu elemanlar programında derz bırakılmaması opsiyonuna izin vermemesi nedeniyle bu modellemede maksimum derz aralığı olan 10 m (30 ft) seçilmesidir.

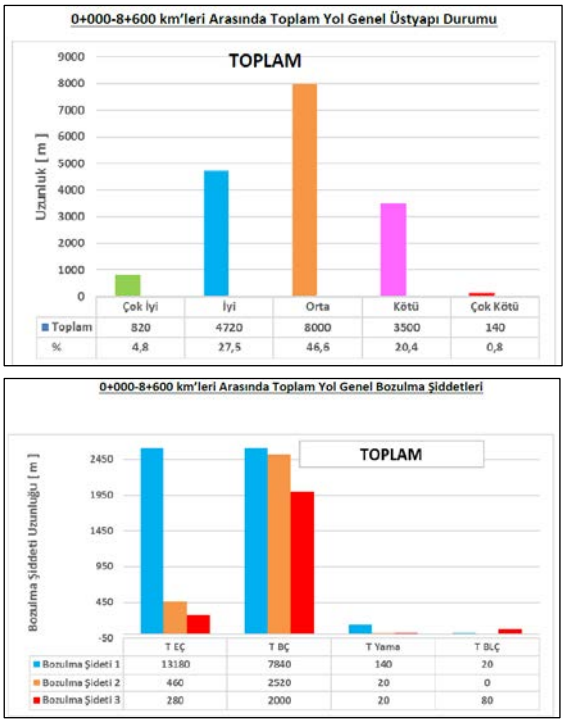


Şekil 3. Mevcut SSB yolu için AASHTOWare PMED modelleme çıktıları (Türkçeye ve metrik sisteme çevrilmiş hali).

Nitekim mevcut Temelli mevki Çokören- Babayakup köyleri arası SSB yolu inşa edilmesinin ardından iki yıl sonra 14.08.2020- 20.08.2020 tarihleri arasında 8,6 km boyunca yol ve çevresi 20 m aralıklara bölünerek yol üstyapısında meydana gelen bozulmalar, bozulma tipleri, şiddeti ve yoğunluğu AASHTO 93 tasarım rehberine göre belirlenerek, yolun iniş ve çıkış eğimleri, yarma/dolgu durumu, zemin sınıfı ve mevcut drenaj sistemleri detaylı şekilde değerlendirilmiştir (Geopave-tcmb_2020/08-02, 2020).

Değerlendirmeler, 2 şerit için de ayrı ayrı yapılarak sağ ve sol şerit olmak üzere bozulma şiddet ve yoğunlukları belirlenmiştir. Değerlendirmeler sonucunda gözlemlenen toplam yol genel üstyapı durumu Şekil 4-a' da, bozulma tipleri ve bozulma şiddetleri Şekil 4-b' de verilmiştir. Burada; EÇ: enine çatlak- yolun merkez aksına dik ve dike yakın açılarla kesişen çatlaklar, BÇ: boyuna çatlak- yolun merkez aksına paralel uzanan çatlaklar, Yama:

mevcut kaplamanın farklı malzemelerle değiştirilmesi, BLÇ: blok çatlak-beton yüzeyinin yaklaşık olarak dikdörtgen parçalara bölünmesini ifade etmektedir. Bozulma şiddeti 1 çatlakların 1 mm'den ince, bozulma şiddeti 2 çatlakların 1 ile 3 mm arasında olmasını ve bozulma şiddeti 3 çatlakların genişliklerinin 3 mm'yi aşması ile bazı kopmaların oluşmaya başlaması olarak tanımlanmıştır.



Şekil 4. Mevcut SSB yoluna ait inşasından iki yıl sonraki üstyapı durumunun değerlendirilmesi (a) SSB yol genel üstyapı durumu(b) SSB yol bozulma şiddeti (Rapor No: GEOPAVE-TCMB_2020/08-02' den uyarlanmıştır).

Şekil 4-a' dan görüldüğü üzere yapılan saha tetkikleri sonrasında mevcut SSB yolun yaklaşık %21'lik kısmının kötü seviyede olduğu görülmekte ve bu kısmın önemli bir kısmı ise Şekil 4-b'den anlaşıldığı üzere boyuna çatlaklar oluşturmaktadır. Enine çatlaklar ise daha çok bozulma şiddeti 1 seviyesinde gözlemlenmiştir. Şekil 5'te saha gözlemleri sırasında çekilen çatlaklara ait bazı görseller sunulmaktadır. Saha gözlemlerinin AASHTOWare PMED performans çıktıları ile uyumlu olduğu görülmektedir. Performans çıktılarında da Şekil 3'ten görüldüğü üzere inşaatın ilk on yılı içerisinde çatlak yüzdesi bakımından mevcut SSB yolun limit değerleri (%15'lik çatlak yüzdesi) aşacağı tahmini yapmaktadır.

Şekil 5. Sahada gözlemlenen mevcut SSB yola ait çatlak görselleri (Rapor No: GEOPAVE-TCMB_2020/08-02' den uyarlanmıştır).

Saha inceleme ekibi tarafından vurgulanan diğer bir ayrıntı ise Babayakup'dan Çokören yönünde sağ şeritte bulunan bozulmaların şiddet ve yoğunluklarının sol şeritte göre daha yüksek olduğudur ki bu durum sağ yolda ağır yüklü araçların yoğun olarak kullanılması ile yarmada bulunmasından kaynaklandığı düşünülmektedir. Babayakup'dan fabrika çıkışına kadar taş ocağından yüklü kamyonlar sağ şeridi kullanmakta, yüksüz kamyon yönü ise yol boyunca Babayakup'dan Çökeren yönünde sol şerit boyunca akmaktadır.

Mevcut SSB yola ait üstyapı performansını olumsuz olarak etkilen bir diğer etmenin ise zemin formasyonu ile ilgili olduğu düşünülmektedir. Yapılan zemin tahkiklerinde kayaç zemin ve Ankara killi zemin olarak iki formasyonun etkin olduğu ve çatlak yüzdelerin zemin tiplerine göre değişiklik gösterdiği raporlanmış ve ayrıca drenaj sisteminin yetersiz olmasının da üstyapı performansını önemli ölçüde etkilediği vurgulanmıştır.

Aynı ekip tarafından 27.04.2022 yılında yapılan saha tetkikleri sırasında da boyuna ve enine çatlak oluşumu ile blok çatlaklar olmak üzere üç farklı bozulma türünün hâkim olduğu gözlemlenmiştir. Ayrıca SSB kaplamasında kireçtaşı agrega kullanılmasından ötürü, cilalanmalar görülmüş ve yüksek ağır trafik koşullarında özellikle yağışlı mevsimlerde yolun kayma dayanımını artırmak için yüzeyin pürüzlendirilmesi tavsiye edilmiştir.

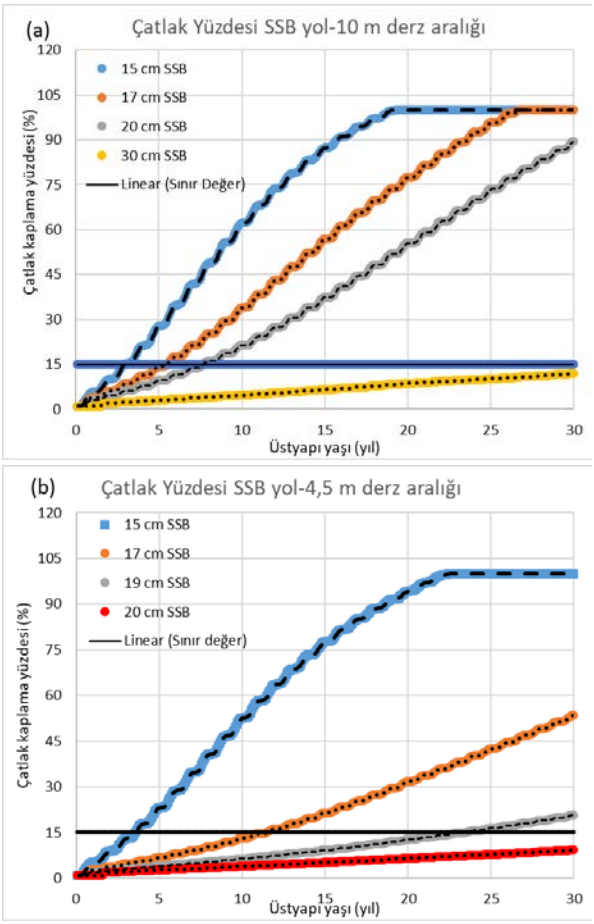
3.2. M-E Yaklaşımla Mevcut SSB Yol Optimizasyonu ve Duyarlılık Analizi

Çalışmanın ikinci aşamasında, Temelli mevki SSB yolunun servis süresi boyunca yeterli performansı göstermesi adına AASHTOWare PMED sonlu elemanlar programı ile tasarım parametrelerin optimizasyonu yapılarak, optimum üstyapı yapısal tasarımı elde edilmeye çalışmıştır. Bu aşamada program performans parametresi olarak sadece çatlak yüzdesi alınmıştır. Bunun sebebi yüzey düzgünsüzlüğünün diğer parametrelere göre saha uygulamasından daha fazla etkilenmesi ve bu nedenle gerçekçi olarak tahmin edilmesinde zorluk yaşanmasıdır. Faylanma parametresinin ise mevcut yolun derz bırakılmadan inşa edilmesi nedeniyle göz ardı edilebilmesidir.

AASHTOWare PMED sonlu elemanlar programı tarafından yapılan optimizasyon çalışmasında, mevcut SSB yolu farklı kalınlıklar için tekrar modellemeleri yapılarak, enine çatlak yüzdesinin servis süresi boyunca sınır değerin altında kalacak yapısal tasarımın bulunması amaçlanmıştır (Şekil 6).

Yapılan yeni modellemeler ile SSB'nin kalınlığı artıkça çatlak yüzdesinde düştüğü görülmüş ve minimum 30 cm'lik bir kalınlıkta SSB yolun servis süresi boyunca çatlak performansı acısından sınır değerler altında kalacağı program tarafından tahmin edilmiştir (Şekil 6-a). İkinci bir alternatif olarak eğer bu mevcut SSB yol günümüzde hem ABD'de hem de bazı son uygulamalar ile Türkiye'de artık yaygınca uygulanan şekilde yaklaşık 4,5 m'lik derz aralıkları ile inşa edilmiş olsaydı Şekil 6-b'den

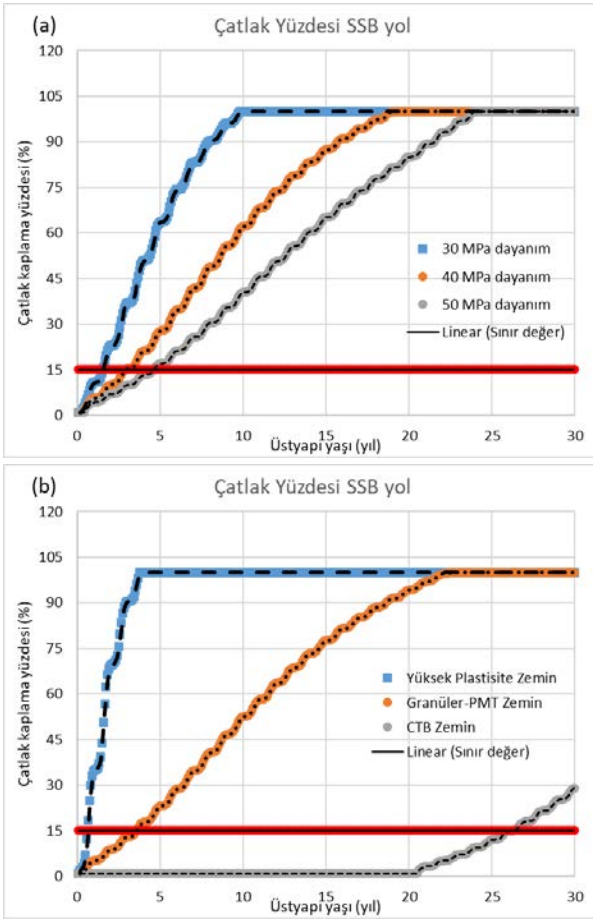
görüleceği üzere 20 cm'lik bir kalınlığın yeterli olacağını göstermektedir ki bu da ilk opsiyona göre %50 da az kalınlık demektir. Buradan da SSB yol tasarımların derz aralıklara karşı oldukça duyarlı olduğu görülmektedir. Ayrıca bu örnekte olduğu gibi bu yöntemle farklı alternatifler geliştirilerek uzun dönemli daha ekonomik tasarımlar yapılabilmektedir.



Şekil 6. Mevcut SSB yolu farklı kalınlar ve (a)-10 m, (b)-4,5 m derz aralıkları için servis süresi boyunca çatlak performans tahmini.

AASHTOWare PMED sonlu elemanlar programına göre, SSB yapısal yol tasarımına etki eden diğer önemli bir parametrenin ise beton dayanımı olduğu Şekil 7-a'da görülmektedir. SSB dayanımı yol çatlak performansını oldukça etkilemektedir. Burada unutulmaması gereken husus mevcut SSB yol tasarım verileri ve kalınlıkları sabit bırakılmış ve sadece SSB beton dayanımı ve malzeme içeriği programda değiştirilmiştir.

Daha önceki analizlerde de vurgulandığı üzere kalınlığın yetersiz olması ve derz bırakılmaması dolayısıyla mevcut yol 30 MPa'lık dayanımda ilk on yılı içerisinde sınır değerleri aşacaktır. Nitekim gerçek saha tetkikleri de bu tahmini doğrulamıştır. Alternatif olarak her şeyin sabit bırakılarak sadece beton dayanımın artırılması çatlak yüzdelerini önemli bir ölçüde azaltmasına rağmen yine de mevcut SSB yolda derz bırakılmaması ve kalınlık yetersizliğinden dolayı inşaatın ilk on yılı içinde çatlak sınır değerlerini aşacağı görülmektedir.



Şekil 7. (a) Farklı beton dayanımları ve (b) temel tiplerinin mevcut SSB yol performansına etkisi

SSB yapısal yol tasarımına etki eden diğer bir parametre ise SSB altındaki temel türünün olduğu Şekil 7-b'den anlaşılmaktadır. Yüksek plastisiteli temel (A-7-6 sınıfı), granüler PMT temel (mevcut temel) ve çimento stabilizasyonlu temel (13500 MPa elastisite modülü) olmak üzere üç farklı temel tipine karşılık SSB yolun servis süresi boyunca çatlak performansı incelendiğinde, zemin tiplerinin üstyapı çatlak performansını ciddi derece etkilediği görülmektedir. Eğer mevcut SSB yolun tüm tasarım parametreleri sabit bırakılarak zemin tipinin granüler temel yerine çimento stabilizasyonlu temelin yapılmış olması özellikle kamyon trafiğinden kaynaklı çatlakları önemli bir miktarda azaltacağı öngörülmektedir. Diğer taraftan yapısal inşaat temelleri için uygun olmayan yüksek plastisiteli (A-7-6 sınıfı) bir zemin temel olarak seçildiğinde ise Şekil 7-b'den görüldüğü üzere yol ilk birkaç yıl içinde tamamen çatlamadan dolayı işletim ömrünü tamamlayacaktır.

4. Tartışma ve Sonuç

Hızlı imal edilebilmesi, erken trafiğe açılması, az bakım onarım gerektirmesi ve ekonomik olması gibi sağlamış olduğu avantajlardan dolayı SSB yol teknoloji ülkemize hızlı bir şekilde adapte olmuş ve 2023 Çevre Şehircilik ve İklim Değişikliği Bakanlığı verilerine göre SSB yol kullanımı kırsal alanlarda 1.000 km'yi geçmiştir (T.C. Çevre Şehirçilik ve İklim Değişikliği Bakanlığı, 2023). Bu

sayıya belediyeler tarafından yapılan uygulamalar da eklenince 5.000 km'yi geçmektedir. Diğer taraftan halen büyük ölçekli olarak geleneksel katalog tasarımı kullanılmakta olup proje özelinde değişiklik gösterecek çevresel, iklim, zemin, malzeme ve trafik koşulları yeterince dikkate alınmamaktadır. Bununla birlikte, özellikle ABD'~~de~~ ve Kanada'da yeni nesil mekanistik-ampirik (M-E) üstyapı tasarım yaklaşımı oldukça yaygınlaşmaktadır. Bu yeni nesil üstyapı tasarımında çevresel iklim etkileri, zemin koşulları, malzeme parametreleri ve trafik verileri yerel şartlara göre kalibre edilebilir transfer fonksiyonlarına bağlı olarak çatlak, faylanma ve düzgünsüzlük gibi üstyapı bozulmalarına dönüştürülebilmekte ve uzun dönemli performans tahminleri yapılabilmektedir. Bu çalışmanın amacı ise Türkiye özelinde Ankara Büyükşehir Belediyesi yol ağında bulunan Ankara ili Polatlı ilçesine bağlı Temelli mevki Çokören- Babayakup köyleri arasında yaklaşık 8,6 km'lik geleneksel yöntemlerle yapısal kalınlık tasarımı yapılan SSB Yol uygulamasının, M-E yaklaşımı ile yeniden tasarımın yapılarak uzun dönemli tahminlerinin yapılması ve gerçek saha performansları ile karşılaştırılmasıdır. Ayrıca bu çalışma kapsamında mevcut SSB yolun tasarımında kullanılan parametrelerin çatlak performansına ne derecede etkili oldukları duyarlılık analizleri yapılarak görülmüş ve tasarım optimizasyonu yapılmıştır. Yapılan analizler sonucu elde edilen bulgular aşağıdaki gibi özetlenebilir.

•Çatlak performansı açısından M-E esaslı AASHTOWare PMED modellemesi, mevcut SSB yolun beş ile on yıl arasında sınır değerleri aşacağını göstermektedir. Bunun en önemli sebebi ise SSB yol uygulaması sırasında derz uygulamasının yapılmamasıdır. Nitekim saha gözlemleri ile bu tahmin doğrulanmıştır.

•Alternatif olarak eğer bu mevcut SSB yol günümüzde ABD'de yaygınca kullanılan 4,5 m'lik derz aralıkları ile inşa edilmiş olsaydı 20 cm'lik bir kalınlıkla (mevcut 17 cm) 30 yıllık servis süresi boyunca çatlak performansı acısından sınır değerler altında kalacağı tahmin edilmektedir.

•Duyarlılık analizlerinde derz aralıklarının yanı sıra, beton dayanımın ve temel tipinin de SSB yol tasarımında etkili olduğu görülmüştür.

•Her şeyden öte tüm İnşaat Mühendisliği uygulamalarında olduğu gibi yol uygulamalarında da işçilik ve saha uygulamaları üstyapı performansını etkileyen en kritik unsur olmuştur. Saha gözlemlerinden yetersiz drenaj uygulamalarının üstyapı performansını oldukça düşürdüğü gözlemlenmiştir.

Sonuç olarak bu çalışma M-E esaslı bir yaklaşımın SSB üstyapı tasarımını daha gerçekçi bir şekilde modelleyebileceğini ve uzun dönemli performans tahminlerini yapabileceğini göstermiştir. Bu şekilde tasarım sürecinde alınan birçok kararın uzun dönemli üstyapı performansına yansıması görülebilecektir. Ancak kullanılan program ABD menşeli olduğu için kalibrasyon katsayıları (mevcut derzli donatısız beton yol performanslarına göre) o ülke koşullarına göre belirlenmiştir ki bu da tahmin etme becerisini hem SSB özelinde hem de Türkiye özelinde düşürmektedir. Ayrıca ticari bir ürün olması nedeniyle dönemlik kullanım ücretleri oldukça yüksektir. Bu çalışmanın uzun dönemli amacı ise SSB yol uygulamaları için ülkemiz özelinde yerel malzeme ve iklim koşulların dahil edilerek, bozulma tahminlerinin daha iyi yapılabilmesi adına mevcut SSB yol uygulamaları ile kalibre edilecek bir M-E esaslı üstyapı tasarım programının hayata geçirilmesi ve kullanıma sunulmasıdır.

Katkı Oranı Beyanı

Yazarın katkı yüzdeleri aşağıda verilmiştir. Yazar makaleyi incelemiş ve onaylamıştır.

	E.Ş.
K	100
T	100
Y	100
VTI	100
VAY	100
KT	100
YZ	100
KI	100
GR	100
PY	100
FA	100

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

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ENHANCING ONLINE LEARNING IN ARCHITECTURAL EDUCATION: A VIRTUAL REALITY ENABLED EXPERIMENT WITH ARKIO

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Abstract: This study examines the role of Arkio, a Virtual Reality (VR) platform, in facilitating design critiques during online learning in first-year architectural design studios. This research, which was conducted after the severe earthquake that required a return to remote education, is based on the experiences of instructors who had previously adapted to online teaching during the Covid-19 pandemic. Arkio provides an innovative solution for the preservation of the quality of architectural education by offering an immersive, real-time environment for design feedback, which is essential in the absence of in-person studio sessions. Using a mixed-methods approach that incorporates surveys and qualitative feedback from students, the study investigates the impact of Arkio on students' understanding of architectural principles, participation in design critiques, and overall learning experience. The results suggest that Arkio was generally well-received for its ability to facilitate critiques and enhance spatial understanding. However, students encountered difficulties with the platform's interface, 3D modeling tools, and file integration. The significance of user-friendly design in educational technologies is underscored by the strong correlation between the perceived educational value of Arkio and its usability, as revealed by cross-analysis. The study identifies critical areas for improvement, despite the fact that Arkio has the potential to significantly transform the critique process in architectural education, particularly in an online setting that is influenced by external disruptions. These insights are essential for the continuous adaptation of VR-driven tools in architectural education, particularly as institutions navigate the complexities of post-pandemic and disaster-responsive remote teaching environments.

Keywords: Arkio, Virtural reality, Online learning, Architectural design studio

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1. Introduction

In the ever-evolving landscape of architectural education, the integration of digital technologies has become more than a mere supplement; it is a transformative force that redefines pedagogical paradigms. Among these technologies, Virtual Reality (VR) stands out as a particularly potent medium, offering unprecedented opportunities for immersive, interactive learning experiences (Kharvari & Kaiser 2022). While the application of VR in architectural education is not entirely novel, its potential for enhancing remote design studio pedagogy remains an underexplored territory. This gap in the literature becomes especially pertinent in the context of first-year architectural design studios, where foundational skills in spatial understanding and design thinking are cultivated.

The objective of this investigation is to assess the efficacy of Arkio, a VR platform, in facilitating design critiques in first-year architectural design studios during online learning. The objective of this research is to examine the ways in which Arkio improves students' comprehension of spatial design, facilitates real-time collaboration, and offers an immersive environment for architectural feedback. The study also aims to determine the advantages and disadvantages of employing Arkio in comparison to conventional online critique methods, with a particular emphasis on the obstacles presented by remote learning environments. The objective of this study is to offer valuable insights into the role of VR in architectural education and to contribute to the broader discourse on digital tools in design pedagogy by analyzing both the quantitative and qualitative data collected from students.

Moreover, the research is contextualized within the larger narrative of the COVID-19 pandemic, which has acted as a catalyst for the accelerated adoption of various educational technologies, including VR.

In the field of architectural education, a variety of VR platforms have been implemented to improve the processes of spatial visualization and design critique. Autodesk Revit Live, Enscape, Unreal Engine, Twinmotion, and Unity Reflect are among the most notable tools. These platforms offer advanced rendering capabilities, immersive walkthroughs, and high-quality

visualizations. Nevertheless, they are frequently designed for professional use, necessitating substantial technical proficiency and high-performance hardware.

Arkio is more practical and accessible for use in educational settings, particularly for design critiques, due to its emphasis on real-time design interaction and feedback, which surpasses the capabilities of tools such as Revit Live and Unreal Engine in the creation of detailed visualizations.

Arkio's primary competitive advantage is its seamless functionality across multiple platforms, including VR headsets, PCs, Macs, iOS, and Android. Arkio is more accessible to a wider range of users than other platforms that are selective about operating systems, as it is compatible with all of them.

This is especially important in hybrid and online learning environments, where not all students may have access to powerful machines. Arkio is particularly well-suited for architectural education due to its simplicity and accessibility, as well as its collaborative capabilities, in contrast to the more intricate alternatives that concentrate on professional architectural visualization in VR.

The entry barrier is further reduced by its compatibility with affordable VR headsets such as Oculus Quest 2, which enables a greater number of users to engage in immersive design critiques without the need for expensive equipment.

1.1. Historical Context of VR in Education

The historical trajectory of VR in educational settings is a compelling narrative that mirrors broader technological and pedagogical shifts. The inception of VR can be traced back to the pioneering work of Ivan Sutherland in the, 1960s, who developed the first head-mounted display system, thereby laying the groundwork for immersive environments (Sutherland, 1968). Initially, VR was primarily employed in high-stakes simulation scenarios (Angulo and Velasco, 2015; Angulo, 2015; Huang et al., 2021), such as pilot training (Johnson et al., 1975) and medical procedures (Zajtchuk and Satava, 1997), where the cost and risk associated with real-world training were prohibitively high (Caro, 1973; Sommer, 2014).

However, the, 1990s marked a significant turning point, as educational applications of VR began to emerge. Fields like science, engineering, and architecture started to explore the potential of VR for pedagogical enhancement (Alvarado and Maver, 1999; Kamińska et al., 2019). Despite these promising developments, the adoption of VR in educational settings was stymied by several factors. The hardware required for immersive VR experiences was expensive, and the development of VR content was a complex task that required specialized skills (Milgram and Kishino, 1994).

The 21st century, particularly the last decade, has witnessed a democratization of VR technology. The advent of more affordable and user-friendly platforms, such as Oculus Rift and HTC Vive, has significantly lowered the barriers to entry (Laurell et al., 2019). This has catalyzed a renewed interest in the integration of VR into various educational contexts, including architectural design studios (Hui et al., 2020; Sirror et al., 2021; Rauf et al., 2021; Hettithanthri and Hansen, 2022). The current generation of VR platforms not only offers more accessible price points but also provides more intuitive user interfaces, making it easier for educators and students alike to engage with the technology (Macnamara, 2017).

Moreover, the rise of web-based VR solutions has further facilitated its incorporation into educational curricula, allowing for more flexible and scalable implementations (Rojas-Sánchez et al., 2023). This democratization has also enabled more empirical research into the pedagogical efficacy of VR, contributing to its growing legitimacy as an educational tool (Rho et al., 2020). VR application in architectural education will be addressed in the following section.

1.2. Case Studies: VR in Architectural Design Studios

The application of VR in architectural design studios has been the subject of numerous case studies, each contributing unique insights into the pedagogical and practical implications of this technology. This section will delve into some of the most notable case studies that have shaped the discourse on VR in architectural education.

In an early study conducted by (Rahimian and Ibrahim, 2011) investigated the application of VR in architectural design studios. The findings revealed that VR enabled real-time collaboration and provided prompt feedback between students and instructors. This augmented the critique process by increasing the dynamism of design interactions and enhancing students' spatial comprehension, which is especially beneficial for first-year architecture students who often have difficulties with abstract design principles.

A study by Dorta et al. (2016) investigated the use of VR for immersive design evaluation. Students in an architectural design studio used VR to present their projects in a more interactive and immersive format, allowing for real-time feedback from both peers and instructors. The study found that the immersive nature of VR enabled a deeper understanding of spatial relationships but also raised questions about the cognitive load imposed on students.

In a unique application of VR, Ibrahim et al. (2021) used the technology to immerse students in historical architectural contexts. This allowed students to explore and analyze architectural styles and structures from different time periods, enriching their understanding of historical influences on modern design. The study concluded that VR could serve as a powerful tool for contextual learning in architectural education.

A recent study by Zhang (2020) focused on the use of VR to simulate different materials in architectural design. The study found that VR could effectively convey the tactile and visual properties of various materials, aiding in the decision-making process during the design phase.

However, the study also noted the limitations of current VR technology in accurately simulating all material properties.

In a unique approach, de Fino et al. (2022) used VR to immerse students in historical architectural settings. This allowed students to understand the spatial dynamics and design considerations of different historical periods. While the study was generally positive about the potential of VR for this type of education, it also cautioned that the technology should not replace traditional methods of study but should be used to complement them.

The potential for architectural education to be transformed by recent advancements in VR has been demonstrated through the enhancement of spatial understanding, the improvement of collaborative design processes, and the enhancement of immersive learning experiences. Arkio and other VR tools enable students to participate in real-time design critiques and provide immediate feedback in a virtual environment, thereby bridging the gap between traditional design methods and digital visualization technologies (Patel and Khan, 2023).

Several studies have emphasized the advantages of VR in architectural education. Kamath et al. (2012) for example, illustrated that VR can effectively connect theoretical learning with real-world applications by providing an interactive platform for creative problem-solving in architecture.

In addition, other studies have investigated the potential of VR to improve student motivation and engagement. Bashabsheh et al. (2019) discovered that VR not only enhanced the enjoyment of building construction courses but also enhanced comprehension of the design process. Similar to this, Chakraborty and Patel (2020) observed that VR enhances communication between students and instructors, resulting in more effective critiques and a more comprehensive understanding of design concepts.

VR has been demonstrated to facilitate a more profound interaction with architectural components in terms of pedagogical approaches. Based on Erkan (2020) observations, VR environments facilitate students' comprehension of the connections between architectural components, thereby facilitating more well-informed design decisions. In VR-based design studios, Aydın and Aktaş (2020) compared two distinct digital ecosystems—medium-oriented and content-oriented—to provide additional evidence. Their research revealed that, although VR tools captivated students and improved their engagement with intricate design tasks, there were obstacles associated with software usability, particularly in terms of efficiency and precision.

As evidenced by Kieferle and Woessner (2019), early-stage architecture students also benefit from VR through improved spatial awareness. They reported that students who engaged with VR environments were more capable of discussing and reflecting on their design intentions. In the same vein, another study underscored that VR technologies equip students with the necessary skills to meet the professional requirements of architecture by providing them with exposure to the most advanced tools within the industry (Williams et al., 2019).

Additionally, Fathallah et al. emphasized that the integration of VR into architectural education has become exceptionally pertinent in the post-COVID era, as remote learning has expedited the integration of digital technologies into design education (Fathallah et al., 2022).

1.3. Future Trends: The Evolving Trajectory of VR in Architectural Design Studios

As VR continues to make inroads into architectural education, it is essential to consider the future trends that are likely to shape this integration. One of the most promising trends is the rise of immersive collaborative design platforms that allow multiple users to engage in real-time design processes within a shared VR environment (Xie et al., 2021). This trend is expected to revolutionize the way architectural design studios operate, fostering a more collaborative and interactive learning experience (Indraprastha, 2023).

The convergence of Artificial Intelligence (AI) and VR is another trend to watch. AI-driven design assistants within VR environments could provide real-time feedback, suggest design alternatives, or even predict the environmental impact of a particular design, thereby enriching the educational experience (Wang, 2023).

The incorporation of haptic feedback and other sensory experiences into VR platforms is on the horizon (Shell et al., 2022). This advancement could provide students with a more tactile understanding of materials and spatial relationships, thereby enhancing the realism and educational value of virtual design studios.

The concept of adaptive learning environments within VR is gaining traction. These are systems that adjust the level of difficulty or the type of tasks presented based on the user's performance and learning style (Coltey et al., 2021). Such adaptive systems could make architectural education more personalized and effective.

The future of VR in architectural design studios is poised for significant transformation, driven by technological advancements, pedagogical innovations, and evolving societal needs.

2. Materials and Methods

The pedagogical effects of Arkio in an architectural design studio were investigated through the use of a mixed-methods research design, which integrated both quantitative and qualitative data collection methods. The research was designed to assess the extent to which the Arkio 1.5 platform enables real-time design critiques and improves the spatial comprehension and collaborative learning experiences of students in an online environment.

2.1. Participants

Participants were chosen from a cohort of first-year architecture students at Dokuz Eylül University, university Architecture department. Students were

invited to join the studio based on specific criteria: a basic understanding of English and proficiency with digital technologies, prior to the commencement of the academic year. The purpose of this invitation to participate was to guarantee that the students who were chosen for the study possessed the requisite skills to interact with Arkio and other digital design tools that would be implemented in the course. Students had already finished a parametric design studio course taught by the same instructor during the first semester, which had given them a fundamental understanding of computational design methods. The 12 students who participated in this study were therefore well-versed in digital tools, rendering them the most suitable candidates for assessing the integration of VR into architectural education in the department.

2.2. Design Study

During the second semester of the students' first year, the investigation was conducted over a six-week period. The instructor provided real-time feedback in an immersive 3D environment as students presented their design projects using Arkio's VR platform each week. The instructor, utilizing Arkio in a fully immersive VR setup, provided in-depth and spatially aware critiques, emphasizing areas for design improvement (Figure 1).

Figure 1. A screenshot of Arkio in an online studio session.

While the critiques were being observed by the students through desktop or mobile devices, they participated in the process by analyzing the feedback and contemplating its relevance to their own designs. This framework enabled students to derive insights from their peers' projects and compare critiques, thereby facilitating both individual and collective learning.

Collaboration and iterative feedback were prioritized in the studio's design. Students were encouraged to present their updated work in subsequent critique sessions and to revise their designs in accordance with the feedback they received. This iterative approach facilitated continuous learning and adaptation, closely resembling the professional practice of architecture.

2.3. Quantitative Data Collection

Quantitative data were obtained through post-session surveys, which utilized a five-point Likert scale (ranging from 1 = strongly disagree to 5 = strongly agree) to evaluate:

The students' overall experience with Arkio - The ease of use and interface navigation - The impact of Arkio on their understanding of spatial relationships - Satisfaction with the real-time critique process and 3D modeling functionalities

The survey data was analyzed using descriptive statistics, with an emphasis on the identification of trends in educational impact, usability, and user experience. This analysis offered an understanding of the extent to which Arkio supported the students' learning objectives and performed as a teaching tool.

2.4. Qualitative Data Collection

Qualitative insights were acquired through open-ended survey questions and interviews, in addition to the quantitative data. Students were able to articulate their subjective experiences, challenges they encountered, and recommendations for enhancing the use of Arkio in design critiques through the use of open-ended questions. A subset of the participants participated in interviews to gain a more profound understanding of specific aspects of the VR experience, including the collaborative dynamics enabled by Arkio and the role of immersion in spatial understanding.

2.5. Statistical Analysis

In order to offer an understanding of the Arkio experience, the quantitative and qualitative data were analyzed concurrently. The distribution of student responses across various dimensions of the study was illustrated using density diagrams and scatter plots to

visualize the quantitative data. Additionally, cross-tabulations were implemented to investigate the correlations between variables, including overall satisfaction and ease of use.

The qualitative data were categorized into key themes. For example, the interviews provided a more comprehensive understanding of the technical obstacles that students encountered, as they provided further exploration of the interface usability challenges that were identified in the survey.

3. Survey Interpretations

3.1. Quantitative Findings

The distribution of student ratings on key aspects, including overall experience, ease of navigation, and 3D modeling capabilities, was visualized using Smooth Histograms. This histogram highlighted the concentration of responses, enabling a comprehension of central tendencies and variability.

Prior to exploring the specific findings, it is crucial to provide a detailed explanation of the manner in which the data is represented in the graphs. The students' evaluations of Arkio's various features, including usability, spatial understanding, and collaboration, are represented on the X-axis of each graph, with a 5-point Likert scale. The density of the students' choices is represented by the Y-axis, which indicates the percentage of students who selected each option in the overall group.

3.1.1. Overall experience with Arkio

The average score of 4.2 was achieved by the majority of students, who rated their overall experience with Arkio between 4 and 5 (Figure 2). This robust positive response suggests that Arkio effectively accommodates the requirements of first-year architecture students. It is important to note that students who found Arkio to be more user-friendly were more likely to provide higher overall ratings. This implies that the user interface is essential in determining the overall user experience, thereby underscoring the significance of intuitive design in educational VR applications.

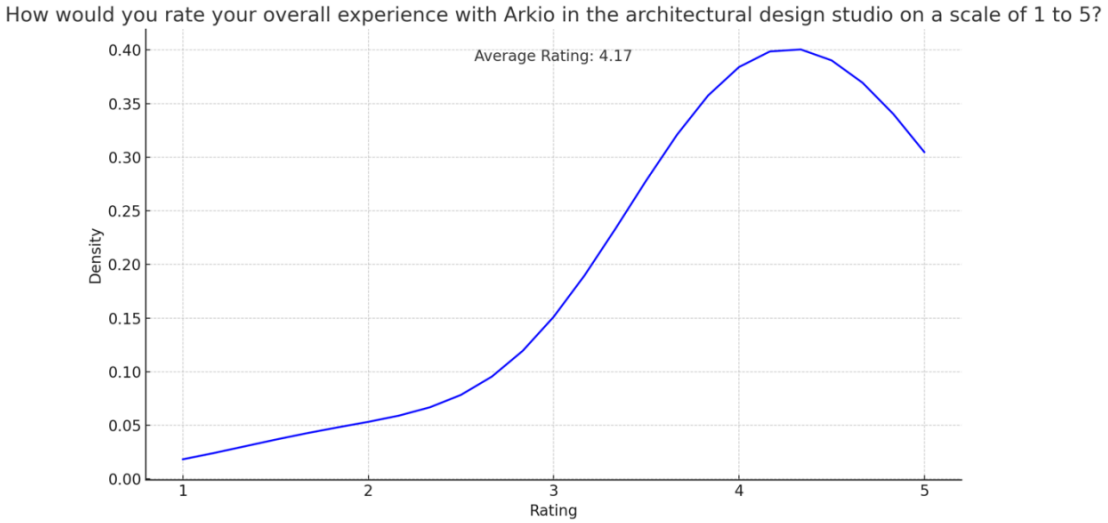

Figure 2. The feedback graph for the overall experience with Arkio.

3.1.2. Simplicity of navigation

The ease of navigation ratings exhibit a greater degree of variability, with scores ranging from 2 to 5, and an average of 3.7. This suggests that while a significant number of students found Arkio's interface to be user-friendly, others encountered difficulties (Figure 3).

The overall experience and other aspects of Arkio were frequently rated lower by students who reported difficulties with navigation (Figure 4). This pattern emphasizes the necessity of interface enhancements, as the overall effectiveness and enjoyment of the tool are closely correlated with user-friendly navigation.

3.1.3. Comprehension of architectural concepts

Arkio had a positive impact on students' comprehension of architectural concepts, as evidenced by their average rating of 4.1. Particularly those who expressed a high regard for Arkio's 3D modeling capabilities were more inclined to report improved comprehension (Figure 5). This correlation emphasizes the significance of reliable 3D modeling tools in enabling a more profound understanding of architectural design principles.

3.1.4. Assessment of 3D modeling capabilities

The average score of 3.8 was obtained for Arkio's 3D modeling capabilities, with responses that encompassed a wide range. Students who found the 3D modeling tools to be effective also tended to rate their overall experience and understanding of spatial design more favorably (Figure 6). This implies that the quality of the modeling features is essential for the technical aspects of the design process and the broader educational outcomes associated with the tool.

3.1.5. The value of real-time 3D comments and critiques

The real-time 3D comments and critiques were generally perceived as beneficial, with an average rating of 3.9, although this was not universally the case. Students who found these critiques more beneficial were more inclined to provide higher ratings for their overall experience and

to recommend Arkio for future use (Figure 7). This suggests that the learning experience is significantly improved by providing timely and constructive feedback within the VR environment. The effectiveness of Arkio as an educational tool could be further enhanced by guaranteeing that this feature is consistently reliable.

3.1.6. The voice chat feature's effectiveness

The voice chat feature was given an average score of 3.7, which is indicative of its significance in facilitating communication during design critiques (Figure 8). Nevertheless, the degree of variability in these ratings indicates that certain students encountered difficulties with the tool's functionality. Those who gave the voice chat a high rating also tended to report a more positive overall experience.

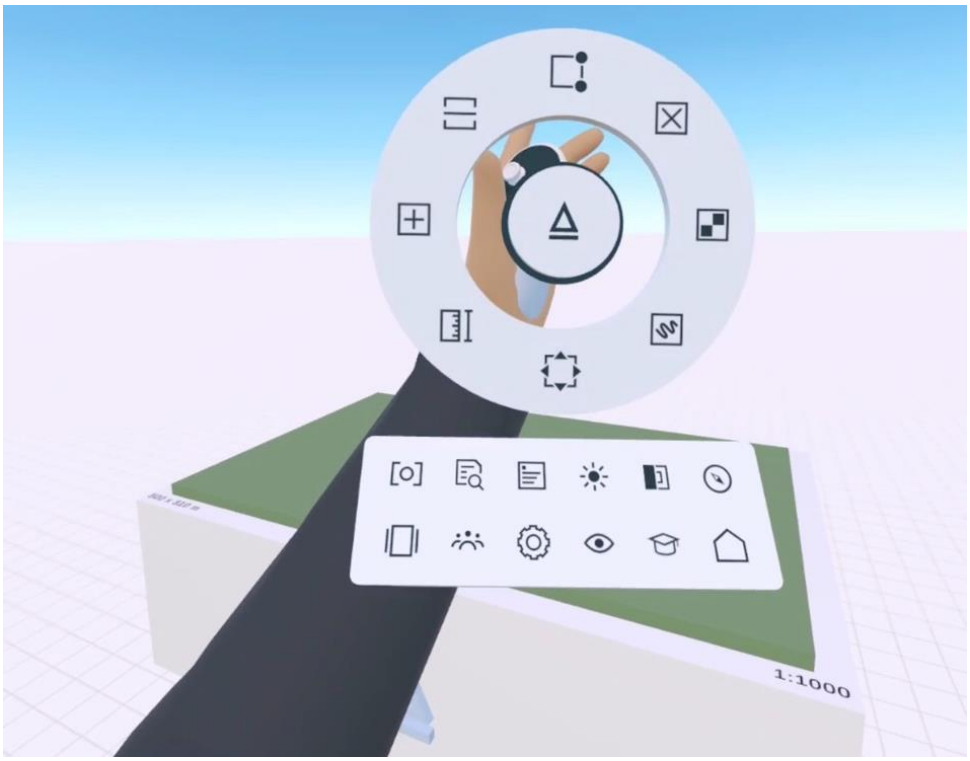

Figure 3. VR user interface of Arkio.

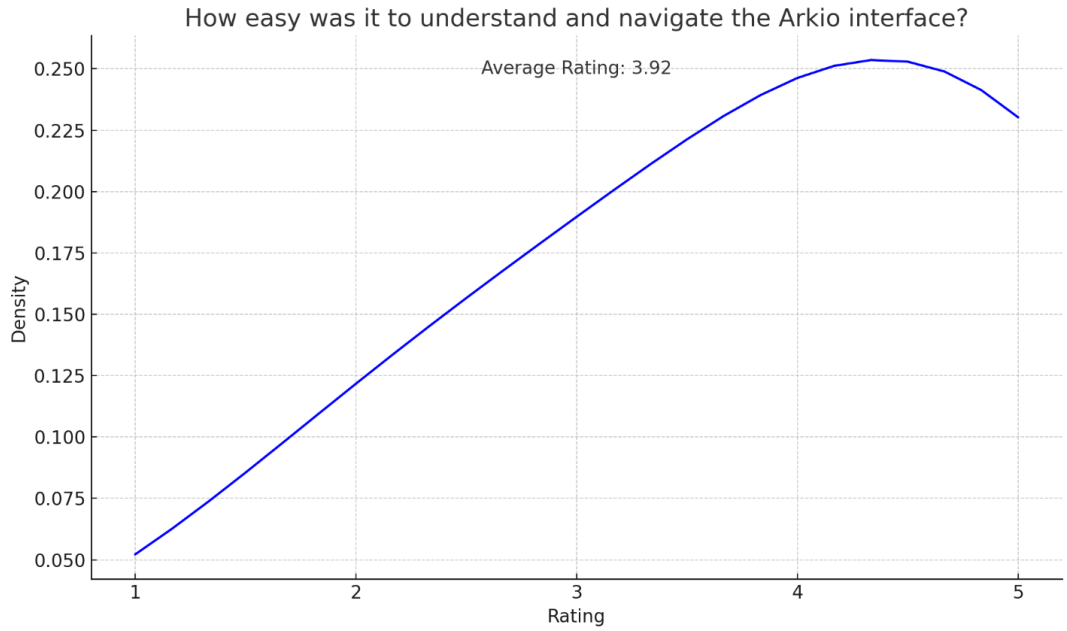

Figure 4. The feedback graph of the navigation in the Arkio interface.

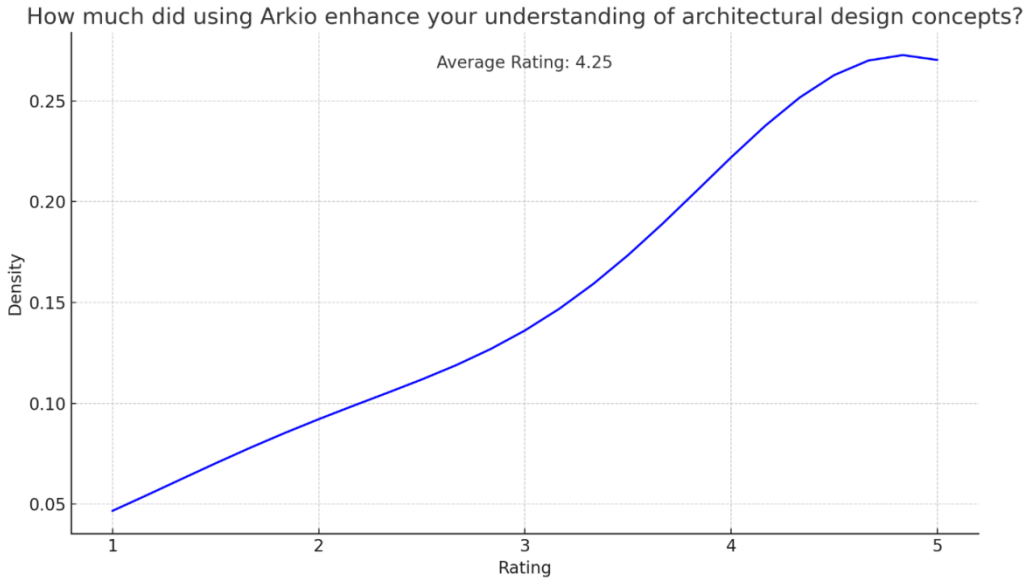

Figure 5. The feedback graph of the software for enhancement of architectural concepts.

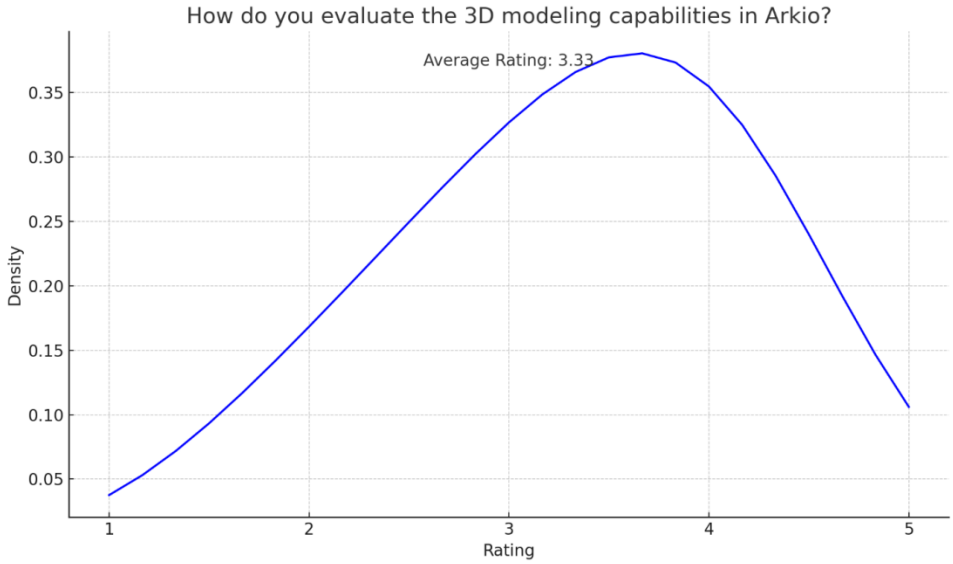

Figure 6. The feedback graph for the usage of modelling capabilities in Arkio.

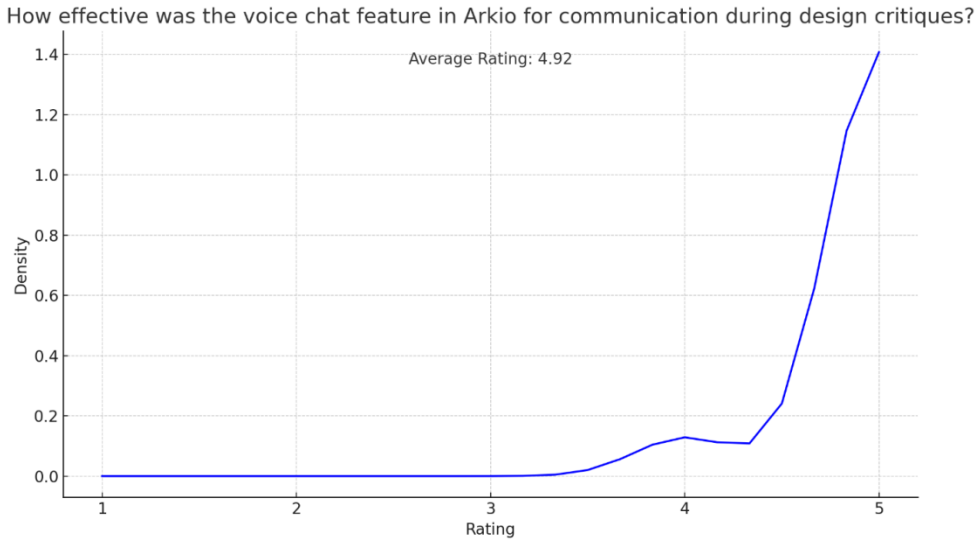

Figure 7. The feedback graph for the success of real-time 3D critiques.

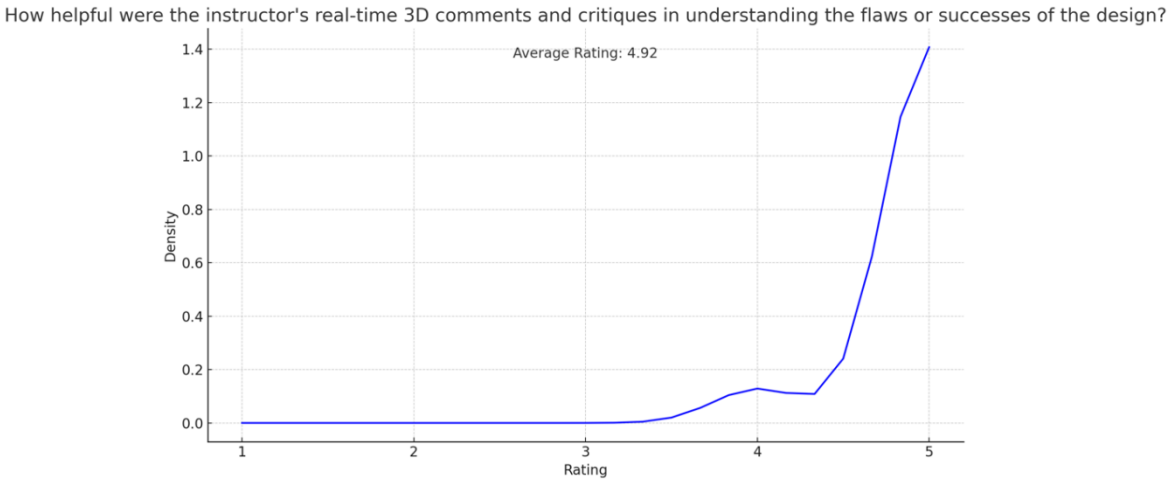

Figure 8. The feedback graph for the effectiveness of the voice chat feature in Arkio.

3.1.7. Arkio's contribution to the development of spatial design

The average score of 4.1 that students assigned to Arkio's contribution to their comprehension of spatial design suggests that the tool effectively facilitates the development of essential architectural skills (Figure 9). Students who found the 3D modeling capabilities to be particularly robust were more likely to report that Arkio assisted them in acquiring a more comprehensive understanding of spatial design. This implies that the immersive and interactive components of Arkio are especially advantageous for grasping and visualizing intricate spatial relationships, which are essential components of architectural education.

3.1.8. Probability of endorsing Arkio

The average rating for the likelihood of recommending Arkio was 4.3, which indicates that students strongly endorse the product (Figure 10). The tool was particularly recommended by individuals who highly rated their overall experience and understanding of spatial design, suggesting that the willingness to advocate for Arkio's use in future design studios is driven by satisfaction with these core elements.

3.1.9. Wide angle view

The juxtaposed graph depicts the distribution of student evaluations for the Arkio software's various features (Figure 11). The user experience is generally positive, as evidenced by the concentration of overall experience ratings in the 4.0 and 5.0 range. The software is largely user-friendly, but some students may encounter challenges. Additionally, the interface ease of use and the enhancement of architectural understanding show a significant concentration around 3.0 and 4.0 ratings.

The evaluation of the effectiveness of voice chat and the capabilities of 3D modeling indicates that the feedback is generally positive, with high ratings. However, there are notable dips at specific rating points that suggest areas where improvements could be made in user interface. Arkio's acceptance as an effective educational tool is particularly evident in the categories of spatial design understanding and recommendation for future use, which exhibit a high concentration of high ratings. In general, these results indicate that Arkio is well-received; however, targeted improvements could potentially enhance user satisfaction in particular domains.

3.2. Correlation Scatter

This study's 3D scatter plot provides a visualization of the correlation between students' overall experience with Arkio, their improved comprehension of spatial design, and their assessment of the software's 3D modeling capabilities (Figure 12). The color coding of the data points denotes distinct clusters of students who share similar experiences and perceptions, with each point representing an individual student.

Various levels of satisfaction and engagement with Arkio are indicated by the clusters, which reveal distinct groupings of students. For example, one cluster may consist of students who highly evaluated both the 3D modeling capabilities and their overall experience, suggesting that these features of Arkio significantly contribute to their improved comprehension of architectural concepts. In contrast, another cluster may exhibit students who rated the 3D modeling capabilities lower, potentially suggesting that the challenges they encountered in this area impeded their overall experience and understanding.

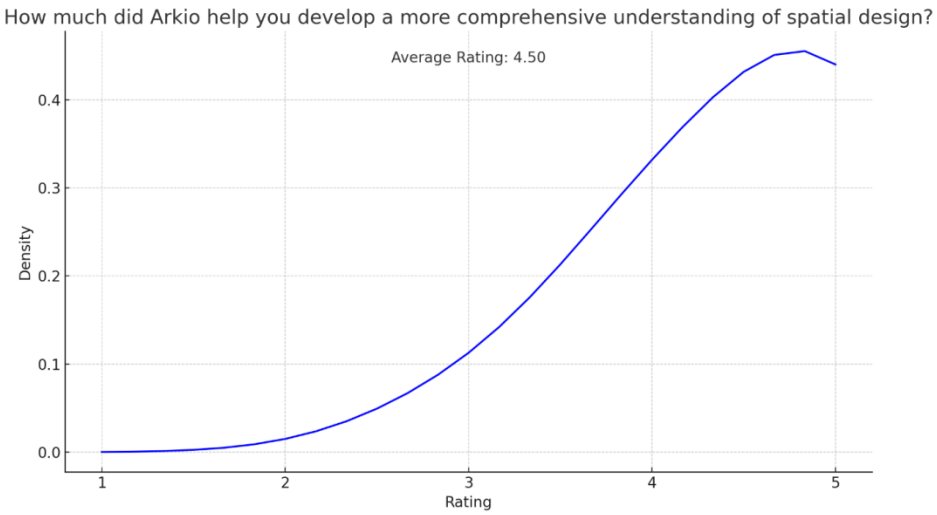

Figure 9. The feedback graph of the effects of Arkio for understanding spatial design.

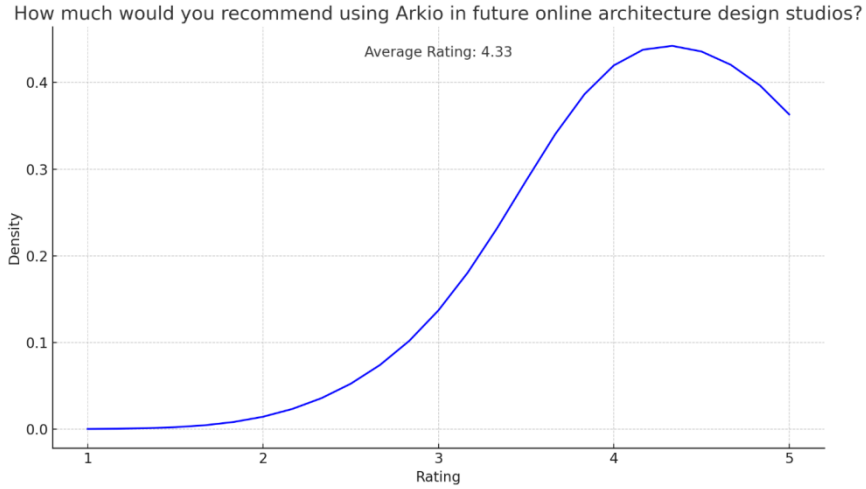

Figure 10. The feedback graph of the recommendation of the software.

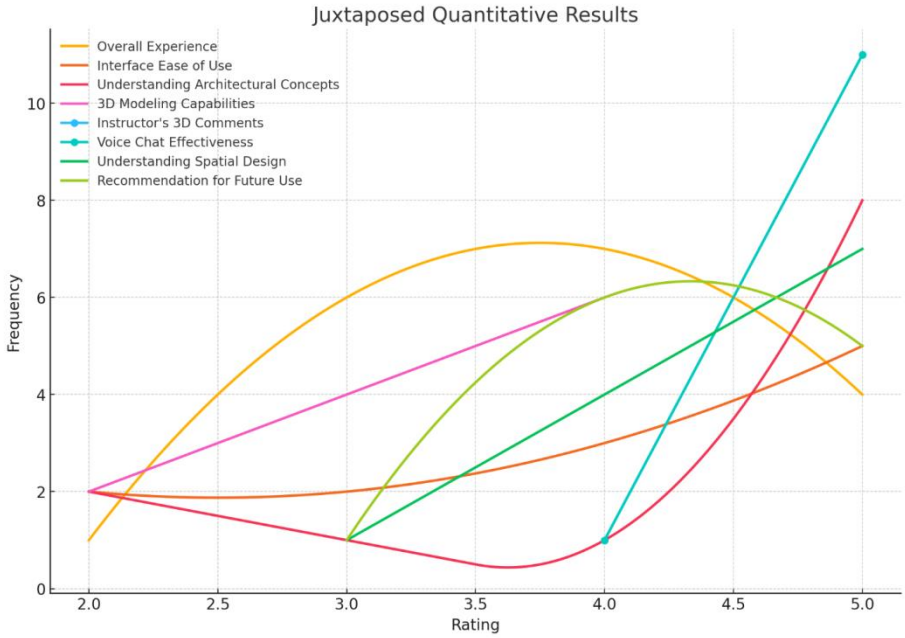

Figure 11. The graph of juxtaposed quantitative answers.

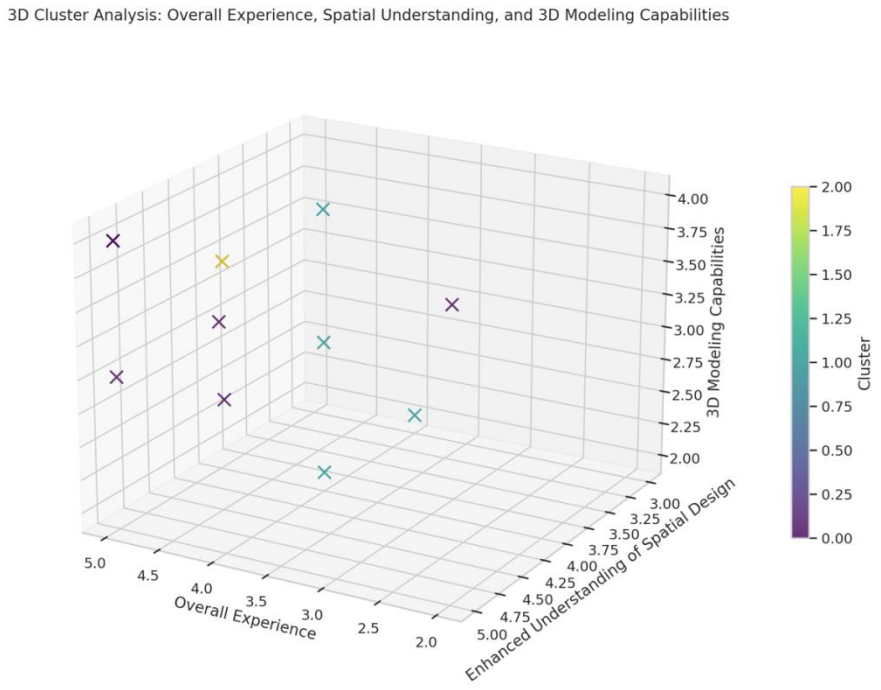

Figure 12. The correlation scatter diagram of quantitative section.

3.3. Qualitative Findings

The qualitative data collected from open-ended questions in the survey provided insights into the students' subjective experiences with Arkio. These findings were analyzed in relation to existing research on the application of VR in architectural education.

3.3.1. Engagement and immersion

Students overwhelmingly reported a heightened sense of engagement and immersion while using Arkio. This corroborates with the work of Dede (2009), who emphasized the role of immersive VR environments in enhancing student engagement. One student noted, "Arkio made me feel like I was part of the design, not just an observer." This sentiment aligns with the concept of 'presence' in VR, as discussed by Slater and Wilbur (Slater and Wilbur, 1997), which refers to the user's psychological immersion in a virtual environment.

3.3.2. Collaborative learning

The platform was praised for its collaborative features, enabling real-time interaction among students and instructors. This resonates with the findings of Gül and Maher, who highlighted the potential of VR to facilitate collaborative learning in architectural education (Gül and Maher, 2006). Students mentioned that the ability to see their peers' designs evolve in real-time was "inspiring" and "motivating," thereby fostering a collaborative learning ecosystem.

3.3.3. Design iteration and feedback

Students appreciated the immediate feedback they received on their designs, stating that it helped them make quick iterations. This is in line with the research by Schnabel who argued that immediate feedback is crucial for the design iteration process in architectural education (Schnabel, 2011). The qualitative data revealed that Arkio's real-time feedback mechanisms were particularly effective in this regard.

3.3.4. Technical challenges

However, some students reported technical glitches and difficulties in navigating the interface, which occasionally disrupted the learning experience. This is consistent with the challenges noted by Kvan (2000), who pointed out that the technical complexities of VR platforms could sometimes act as barriers to effective learning.

Arkio's interface, particularly the importation of 3D models and file transfers, was the subject of numerous student complaints. One student stated, "We encountered difficulty in comprehending the process of uploading our 3D models during the initial phase," while another student acknowledged, "I encountered difficulties in importing my design from an alternative application." These challenges indicate that Arkio offers valuable features; however, there is a learning curve and certain technical limitations that must be resolved in order to facilitate their 3D file integration.

The technical challenges that students face, including the complexity of the interface and issues with file transfers, are indicative of the common obstacles that arise when integrating VR tools into educational environments. The immersive learning experience that VR aims to provide can be compromised by these technical limitations. Therefore, it may be essential to address these issues through future updates or user training in order to improve Arkio's effectiveness in architectural education.

Additional recommendations included the development of instructional videos and the improvement of the software's drawing tools, which could result in critiques that are more comprehensible and effective. These observations underscore the significance of adequately

preparing students prior to the use of intricate VR tools such as Arkio and guaranteeing that the software's capabilities are intuitive and user-friendly.

3.3.5. Pedagogical implications

The qualitative findings also touched upon the pedagogical implications of using Arkio. Students felt that the platform had the potential to revolutionize traditional teaching methods in architectural design in online learning, a sentiment that echoes the transformative potential of VR in education as discussed by Mikropoulos and Natsis (2011).

By contextualizing these qualitative insights within the framework of existing literature, we gain a multi-dimensional understanding of Arkio's impact on architectural education. These findings not only validate the platform's efficacy but also highlight areas for future research and development.

4. Results

Insights into the impact of Arkio, a VR tool, on the architectural education experience of students, particularly in the context of online learning and design critiques, are provided by the findings of this study. In order to evaluate the overall effectiveness of Arkio in facilitating real-time, immersive critiques, learning outcomes, and usability, both quantitative and qualitative data were collected.

4.1. Effect on Spatial Understanding

One of the primary goals of this investigation was to assess the extent to which Arkio enhanced students' understanding of spatial relationships, a critical component of architectural education. The quantitative data, which were obtained through post-session surveys, suggest that the majority of students gave Arkio a high rating for its capacity to improve their spatial comprehension (Figure 9).

4.2. Navigation and Usability

The study also prioritized Arkio's usability. The quantitative results were more inconsistent, with usability ratings ranging from 2 to 5 . The interface was intuitive for students who were already familiar with digital tools, but those with less experience reported initial difficulties in navigating the platform. Nevertheless, the interface became more familiar to the majority of students after a few sessions.

4.3. Real-Time Feedback and Collaboration

Arkio's capacity to enable real-time collaboration and feedback is a significant benefit when utilizing it in architectural education. Arkio facilitated more dynamic interactions during critiques, which enabled students to observe design changes in real-time and more effectively comprehend the instructor's feedback, according to their reports. This was especially advantageous for students who were previously unfamiliar with collaborative design tools. The real-time feedback feature was deemed highly valuable in the critique process by the majority of students (85%).

4.4. Technical Challenges and Opportunities for Improvement

Although Arkio was generally well-received, a number of students encountered technical difficulties, particularly those associated with the import of 3D models and the interface's complexity. The file import feature of the platform was the source of frustration for approximately 30% of the students, who claimed that it was difficult to integrate their designs from other software into

4.5. Influence on Architectural Education

The results indicate that VR tools such as Arkio provide significant advantages by allowing students to experience their designs in a more immersive and interactive manner, a feat that is challenging to accomplish through conventional critique methods. Furthermore, Arkio promoted a more collaborative atmosphere in which students could interact with their instructors and peers in real time, thereby enabling more constructive and dynamic feedback, particularly in online learning environment.

90% of students concurred that Arkio enhanced their architectural education, particularly in terms of their capacity to refine and visualize their designs, in terms of the overall learning experience. Nevertheless, the technical obstacles encountered, particularly those associated with model imports and usability, underscore the necessity for additional refinement.

5. Discussion

The incorporation of VR into first-year architectural design studios offers students an immersive, interactive environment that has a substantial impact on their learning experiences, particularly in the areas of collaborative design and spatial understanding.

This discussion is consistent with the current body of literature, which underscores the potential of VR to facilitate the development of spatial reasoning, a critical skill in architectural design (Carbonell-Carrera et al., 2021; Darwish et al., 2023). This benefit is less pronounced in traditional two-dimensional design tools, as the ability to navigate and interact with design models in a three-dimensional space enables students to more effectively comprehend intricate spatial relationships.

Additionally, the research underscored the collaborative potential of VR environments in Arkio. The capacity to collaborate in a shared virtual space provides a new dimension to team-based projects, as the emphasis on collaborative learning in architectural education continues to grow. The collaborative nature of professional architectural practice is reflected in the ability of students to participate in real-time critiques and modifications.

Conversely, the investigation disclosed numerous technical obstacles encountered by the students, including the navigation of the Arkio interface, the utilization of its 3D modeling tools, and the management of file integrations. These challenges are consistent with those reported in other educational contexts that involve

VR, indicating that while VR technology has potential, it also necessitates implementation to prevent it from impeding the learning process (Shih et al., 2019).

The study's methodological approach, which integrated both quantitative and qualitative data, enhanced the findings and offered a comprehension of the educational implications of utilizing Arkio. Nevertheless, the relatively small sample size of 12 students is a constraint, and future research could be enhanced by incorporating a more diverse and extensive cohort of students. Moreover, the findings are further complicated by the study's distinctive context, which was conducted in the aftermath of a significant earthquake and during a period of ongoing adaptation to post-COVID-19 online learning.

6. Conclusion

In summary, this investigation offers empirical evidence that bolsters the integration of VR, specifically Arkio, into architectural design education. The results suggest that VR can significantly improve students' spatial comprehension and facilitate more effective collaboration in design critiques, particularly in online learning environments.

Despite Arkio has the potential to significantly improve design critiques in architectural education, the technical challenges that the students have identified—particularly those related to the user interface and file imports—suggest that additional refinements are necessary to achieve optimal usability. Arkio can be even more transformative in architectural education by addressing these issues and implementing student suggestions, such as improving drawing tools and user interface, as online and hybrid learning environments continue to evolve.

Although the potential advantages of VR in architectural education are evident, the study also underscores the necessity of planning and phased implementation to address technical obstacles. As the accessibility to the hardware, students become more accustomed to the VR environment, educators should consider beginning with simpler tasks and gradually introducing more complex projects. This method has the potential to mitigate the learning curve and guarantee that students can fully capitalize on the capabilities of VR tools such as Arkio.

Comparative studies that involve multiple VR platforms could provide valuable information on the relative strengths and weaknesses of different tools, and larger, more diverse samples would provide more generalizable insights. In addition, research on the influence of VR on other aspects of architectural education, such as student motivation and design creativity, would further improve our comprehension of its pedagogical worth.

In conclusion, the incorporation of VR into architectural design education is a substantial advancement in the adaptation of teaching methods to the needs of a world that is rapidly evolving. It is imperative that educators remain cognizant of the obstacles and approach implementation with a thoughtful approach as they continue to investigate the potential of VR. This research contributes to the expanding body of literature on the pedagogical applications of VR and provides educators in the field of architecture with actionable insights, thereby facilitating the development of more innovative and effective teaching practices in the future.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	E.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

The author confirms that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. All participants filled out informed consent forms in the study.

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AN OPTIMIZED PID CONTROLLER DESING FOR BLDC MOTOR USING NATURE-INSPIRED ALGORITHMS

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Abstract: For the optimal control of speed in a brushless DC motor, it is crucial to appropriately adjust the parameters of the PID controller. This study addresses the determination of PID controller parameters using nature-inspired metaheuristic optimization algorithms. Initially, the dynamic model of the brushless DC motor is formulated in the MATLAB/Simulink environment. The grey wolf optimization algorithm, whale optimization algorithm, and firefly algorithm are successively applied to the simulation model to optimize the PID controller parameters. The integral time absolute error objective function is utilized to compare the error performances of these algorithms. Additionally, performance evaluations are conducted concerning parameters such as rise time, settling time, and maximum overshoot. As a result of the comparison based on the fitness criteria, it was determined that the grey wolf optimization algorithm is 35% more successful than the algorithm that provided the next closest result.

Keywords: Brushless DC motor, Nature-inspired algorithms, PID control

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1. Introduction

DC motors are efficient electrical machines with ideal operating characteristics for variable speed drives. Their most significant disadvantage is the requirement for a commutator and brushes, both of which wear out and need replacement. Maintenance-free, efficient motors can be obtained by using solid-state switches that take on the role of the commutator and brushes. These motors are called brushless direct current (BLDC) motors (Ehsani et al., 2021; Chittajallu and Lanka, 2023). A BLDC motor consists of three-phase concentrated windings on the stator and permanent magnets on the rotor. Commutation is electronically achieved using a three-phase static inverter powered by a continuous DC source. The Hall sensor serves as a position sensor and is mounted on the stator (Santra et al., 2022; Potnuru et al., 2022; Çetintaş et al., 2023). Due to their characteristics such as high dynamic response, efficiency, silent operation, high torque, and low volume, the use of BLDC motors is increasingly prevalent in many industrial applications. Additionally, in cases where space and weight are critical, they are preferred due to the larger torque provided per motor size. In this study, a control strategy is proposed for the speed control of BLDC motors. PI controllers are simple and widely used for many industrial applications. When BLDC motors are considered as a system, there are uncertainties in their mathematical model due to their advanced nonlinear structures. Therefore, achieving the best performance when tuning PI controller parameters using traditional methods is challenging. Among the traditional tuning methods, Ziegler-Nichols is the most well-known. However, manual tuning can take longer and may potentially damage the hardware during the control process. Moreover, rule-based approaches may not cope well with certain high-level systems. In many current applications, optimization-based techniques developed with a specific objective function are utilized for tuning the parameters of PI or PID controllers.

The study compares the control of a BLDC motor using a traditional PI controller with artificial neural network-based control in a simulation environment (Ch and Palakeerthi, 2015). It was found that the artificial neural network controller exhibited superior performance compared to the PI controller in tracking speed reference changes and stabilizing output speed during load variations. It is addressed the optimization of the commutation angle of the BLDC motor and its impact on speed, current, efficiency, and noise spectrum (Bober, 2017). It is aimed to minimize losses, production costs, and motor volume by optimizing geometric parameters in the design of BLDC motors, utilizing methods such as cuckoo search, genetic algorithm, and particle swarm optimization (Azari et al., 2017).

It is tackled the issue of the inability to adapt to parameter adjustments and system behavior changes encountered in speed control of BLDC motors with a PI controller (Praptodiyono et al., 2020). An optimal adaptive PI controller combining particle swarm optimization and fuzzy logic control was proposed. It is

presented the determination of the optimal PI parameters for speed control of a permanent magnet synchronous motor using six swarm intelligence-based optimization algorithms and compared their performances (Aguilar-Mejía et al., 2020). It is utilized algorithms like the equilibrium optimizer (EO), grey wolf optimizer (GWO), and whale optimizer (WO) to maximize the efficiency of BLDC motors and minimize total mass for optimal design (Premkumar et al., 2021).

It is proposed an effective controller design for BLDC motor drivers using the nature-inspired whale optimization algorithm (WOA) (Chittajallu and Lanka, 2023). PI controller parameters were optimized using WOA with integral square error (ISE) as the objective function, resulting in improved performance of the controller. It is addressed the optimization of PID controller parameters controlling the speed of a permanent magnet BLDC motor using metaheuristic algorithms (Abdolhosseini and Abdollahi, 2023). The performance of 14 different algorithms was observed considering settling time, rise time, overshoot, and step response stability of the system. It is suggested a particle swarm algorithm-adjusted fuzzy logic-PI controller for speed control of BLDC motors (Jun et al., 2022). The performance of the optimized PI controller was measured using Integral Absolute Error (ITAE), Integral of Time-Squared Error (ITSE) and ISE error-based performance indicators, demonstrating superior performance.

It is proposed an equilibrium optimization algorithm-based fractional-order PID controller as a solution to sudden set point and parameter changes in traditional PID control of BLDC motor speed (Temir and Durmuş, 2023). The performance of the proposed equilibrium optimization algorithm in optimizing controller parameters was compared with particle swarm optimization (PSO), differential evolution (DE), and golden jackal optimization (GJO) algorithms, showing better results. In this study, a newly proposed metaheuristic optimization algorithm, WOA, was used to optimize PID gains for non-linear BLDC motors.

The optimization algorithms mentioned in the literature review can be applied to various optimization problems, but they exhibit different performance characteristics depending on their attributes and the specific problem being addressed. This performance can vary between good and poor, and understanding this is crucial. From this perspective, there is a need for a comparative study that evaluates some popular optimization algorithms used for optimizing the speed controller of BLDC motors.

In this study, speed control of the BLDC motor is achieved in a simulation environment utilizing the PID method and metaheuristic algorithms. These algorithms comprise the GWO, WOA, and FA (Firefly Algorithm), respectively. The reason for selecting these algorithms, which are frequently encountered in the literature, within the scope of this study is their novel and competitive nature. Performance comparisons of the algorithms used for determining PID parameters are conducted in detail, and the results are presented in the results section. In order to perform a dynamic simulation of a brushless DC motor, its mathematical model must be derived. The subsequent Section 2 provides an in-depth examination of the mathematical model of the BLDC motor, detailing specific aspects related to its dynamic modeling. Section 3 elaborates on the BLDC model created in the MATLAB/Simulink environment and the algorithms utilized. Experimental studies and the obtained findings are analyzed in detail in Section 4, followed by a discussion of the results in Section 5.

2. Materials and Methods

The modeling of the BLDC motor can be developed similarly to a three-phase synchronous machine. Due to the rotor being mounted with permanent magnets, certain dynamic characteristics differ. The equivalent circuit of the BLDC motor, shown in Figure 1, includes a permanent magnet mounted on the rotor and three stator phase windings connected in a star configuration. The motor is powered by a three-phase voltage source. Not only sinusoidal but also square wave or even other waveforms can be applied. The modeling of the BLDC motor is based on several assumptions:

(i) The motor is unsaturated and should operate with rated current.
(ii) The resistances of the three stator phase windings are equal.
(iii) Self-inductance and mutual inductance are constant.
(iv) Iron and copper losses are negligible.
(v) The three phases are balanced.
(vi) Uniform air gap.
(vii) Hysteresis and eddy current losses are neglected.
(viii) Semiconductor switches are ideal.

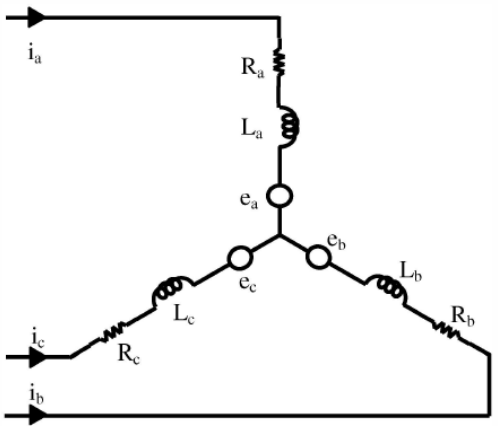

Figure 1. Equivalent circuit of a BLDC motor.

BLDC motors are equipped with a rotor containing permanent magnets and trapezoidal electromotive force (EMF) (Mondal et al., 2015). Typically, a three-phase inverter is used to drive BLDC motors, requiring the utilization of a rotor position sensor element for the operation of the inverter module. The three-phase

inverter employs a six-step commutation mechanism to drive the BLDC motor. Position sensors should be employed for the proper commutation sequence, and initially, Hall effect sensors should be utilized. Within each phase, there will be an interval of 120° between executions.

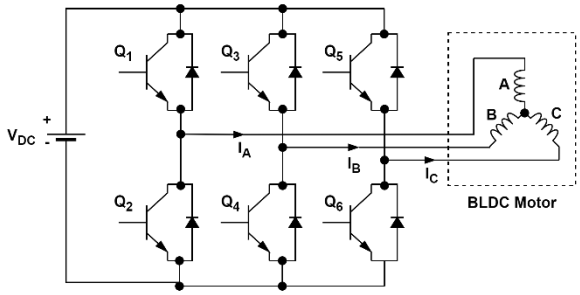

Figure 2. Three phase simplified Inverter.

As depicted in Figure 2, the execution sequence will be 1-4, 1-6, 3-6, 3-2, 5-2, and 5-4. The applied current defining the operation of a BLDC motor should be synchro-nous with the back electromotive force voltage signal. The resultant currents are rectangular in shape, and the motor's switching operation consists of six different steps controlled by a six-step control mechanism. The rotational position can be determined either by position sensors or sensorless methods (Mahmud et al., 2020). The model of the armature winding of a BLDC motor is expressed as follows (equations 1, 2 and 3):

$$V_a = Ri_a + L\frac{di_a}{dt} + e_a \quad (1)$$

$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \quad (2)$$

$$V_c = Ri_c + L\frac{di_c}{dt} + e_c \quad (3)$$

In this context, $R_a = R_b = R_c = R$ represents the stator resistance per phase, $L_a = L_b = L_c = L$ represents the stator inductance per phase, V_a, V_b, and V_c denote the stator phase voltages, i_a, i_b, and i_c represent the stator phase currents, and e_a, e_b, and e_c denote the Back Electromotive Forces (Back EMF) of the motor. The expression of the BLDC motor equation in matrix format is as follows (equation 4):

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R+pL & 0 & 0 \\ 0 & R+pL & 0 \\ 0 & 0 & R+pL \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

In this context p represents d/dt. When a BLDC motor rotates, each winding generates a voltage known as Back EMF, which opposes the main voltage supplied to the winding according to Lenz's law. The polarity of the Back EMF is opposite to that of the source voltage. The direction of the Back EMF is related to the rotor position function, and there is a 120-degree difference between each phase. The Back EMF is primarily dependent on three factors: (i) the angular speed of the rotor, (ii) the magnetic field generated by the rotor magnets, (iii) the number of turns in the stator windings. The equation for each phase is as follows (equations 5, 6 and 7):

$$e_a = k_e . \omega . f(\theta) \quad (5)$$

$$e_b = k_e . \omega . f\left(\theta - \frac{2\pi}{3}\right) \quad (6)$$

$$e_c = k_e . \omega . f(\theta + \frac{2\pi}{3}) \quad (7)$$

Where, k_e represents the Back EMF constant [V/rad/s]. θ denotes the electrical rotor angle. ω stands for the mechanical speed of the rotor [rad/s]. The permanent magnet also influences the torques generated due to the trapezoidal flux linkage. Considering k_t as the torque constant, the generated torques is as follows (equations 8, 9 and 10):

$$T_a = k_t . f(\theta) . i_a \quad (8)$$

$$T_b = k_t . f\left(\theta - \frac{2\pi}{3}\right) . i_b \quad (9)$$

$$T_c = k_t . f\left(\theta + \frac{2\pi}{3}\right) . i_c \quad (10)$$

The total torque, denoted as T_e, can be represented as the simulation of each phase. Consequently, the equation for total torque can be defined as follows (equation 11):

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega} = T_a + T_b + T_c \quad (11)$$

In order to establish the complete mathematical model of an electromechanical system, it is necessary to introduce the motion equations of the motor. At this point, the generated electromagnetic torque in motion can be expressed as follows (equation 12):

$$T_e = J\frac{d\omega}{dt} + T_L + B\omega \quad (12)$$

Where, J represents the rotor inertia [kgm2], and B is the damping constant with T_L load torque, unit N-m. If the Laplace transformation of the equations pertaining to phase a is written, it will be as follows (equations 13, 14, 15 and 16):

$$V(s) = (R + sL) + E_a(s) \quad (13)$$

$$E_a(s) = k_e \omega(s) \quad (14)$$

$$T_e(s) = k_t I_a(s) \quad (15)$$

$$T_e(s) = T_L(s) + (B + sJ)\omega \quad (16)$$

The rotor speed ω is determined as follows using the superposition method (equation 17):

$$\omega(s) = \frac{k_t V(s)}{(R+sL)(B+sJ) + k_t k_e} - \frac{(R+sL)T_L(s)}{(R+sL)(B+sJ) + k_t k_e} \quad (17)$$

Assuming the motor is running without load and considering the conditions $B = 0$ and $T_L = 0$, the following reduced equation 18 is obtained.

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{k_t}{sJ(R + sL) + k_t k_e} = \frac{1}{k_e\left(s^2 \frac{LJ}{k_t k_e} + s\frac{RJ}{k_t k_e} + 1\right)} \quad (18)$$

According to the equation above, the mechanical time constant (τ_m) and the electrical time constant (τ_e) are defined as follows (equation 19):

$$\tau_m = \frac{RJ}{k_t k_e}, \tau_e = \frac{L}{R} \quad (19)$$

With the definitions, the transfer function of the motor is expressed as follows (equation 20):

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{1}{k_e\left(s^2 \frac{LJ}{k_t k_e} + s\frac{RJ}{k_t k_e} + 1\right)} = \frac{1}{k_e(s^2\tau_m\tau_e + s\tau_m + 1)} \quad (20)$$

The parameters of the permanent magnet BLDC motor modelled for utilization in the simulation are provided in Table 1.

Table 1. Parameters of the Brushless DC (BLDC) Motor (Khubalkar et al., 2016)

Parameters	Values	Specification
V	48 V	Voltage
R	2.870 Ω	Stator resistance/phase
L	2.7 mH	Stator inductance/phase
J	0.0005 kg-m²	Moment of inertia
k_t	0.042 Nm/A	Torque constant
k_e	0.042 V/rad/s	Back EMF constant
np	4	Number of poles

After substituting all parameter values from Table 1 into equation 21, the transfer function of the BLDC motor is obtained as follows (Abdolhosseini and Abdollahi, 2023; Khubalkar et al., 2016):

$$G(s) = \frac{\omega(s)}{V(s)} = \frac{1}{3.214 \cdot 10^{-4}s^2 + 0.3423\, s + 0.0042} \quad (21)$$

2.1. Control and Optimization

2.1.1. PID controller

The PID controller, widely employed across diverse systems worldwide, is a linear controller renowned for its typically simplistic and robust architecture, as well as its propensity for delivering satisfactory performance outcomes. The output of the PID controller is defined by the following tracking equation 22.

$$U_{PID} = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \quad (22)$$

Where, the control parameters k_p, k_i, and k_d are proportional, integral, and derivative gains respectively, while *e(t)* represents the error (Joseph et al., 2022; Demir and Demir, 2023). PID controllers measure the output error via a feedback loop and generate the control signal by combining three main control terms: Proportional, Derivative, and Integral. The ability of the PID controller to demonstrate the desired performance relies on the proper tuning of its parameters. Various methods exist for parameter tuning, ranging from classical methods requiring mathematical modeling and analysis of system response to techniques based on metaheuristic optimization algorithms for finding optimal parameter values of PID controllers (Nisi et al., 2019).

Among the classical PID controller tuning methods, the Ziegler-Nichols method, Chien-Hrones-Reswick (CHR) method, Cohen-Coon method, Integral Performance Criterion (IMC), and gain and phase margin-based design methods are the most well-known. These methods attempt to find suitable values for controller parameters utilizing the mathematical model of the system. However, these methods require accurate and complete knowledge of the system model, and sometimes experimentation and adjustments may be needed to achieve the desired performance.

PID controller tuning methods based on optimization algorithms use metaheuristic algorithms to optimize controller parameters. These methods typically require the system's mathematical model or detailed analysis. Additionally, they can automatically adjust controller parameters. However, the optimization process can sometimes lead to computational complexity and require high processing power. The choice of which PID tuning method to use should be determined based on system characteristics, performance requirements, and available data (Águila-León et al., 2020).

Figure 3 illustrates the tuning structure of the PID controller. The adjustment of k_p, k_i, and k_d parameters of the PID controller using an intelligent metaheuristic to optimize the objective function is depicted in Figure 3. The output of the controller (control voltage) controls the speed of the motor.

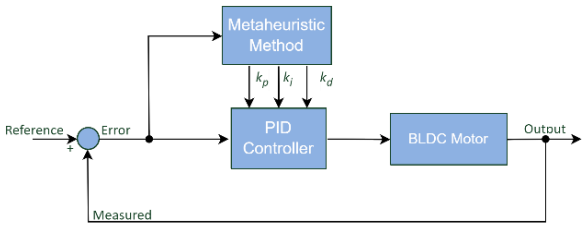

Figure 3. The block diagram of the control system.

2.1.2. Optimization

Optimization problem solutions that satisfy all constraints are feasible solutions. Optimal solutions may encompass objectives such as minimizing the cost of a process or maximizing the efficiency of a system. Control theory deals with dynamic systems and optimizations over time. Therefore, the aim is to find a control for a dynamic system, thus optimizing an objective function. Nature-inspired metaheuristic optimization algorithms can be employed for tuning parameters in PID control applications. Common tasks of these optimization algorithms include randomly selecting initial solutions, evolving solutions based on a fitness function, eliminating the worst solutions, and generating new solutions. The manner in which new solutions are generated constitutes a fundamental difference among these algorithms. It may be desired to assess the im-pact of these algorithms on control. In this case, system performances such as over-shoot and settling time are considered. In multi-objective problems, dynamic error-based performance indices are used instead of multiple fitness functions. These include IAE, ITAE, ISE, and ITSE (Demir and Demir, 2023). In this study, the ITAE performance criterion given in equation 23 is determined as the fitness function to be minimized.

$$f_{ITAE} = \int_0^T t|e(t)|dt \tag{23}$$

When compared with performance indices such as the IAE or the ISE, the ITAE performance index exhibits smaller oscillations and overshoots. Moreover, it possesses greater sensitivity and better selectivity. Additionally, it enjoys computational advantages over the ITSE index. The speed control of a BLDC motor is treated as an optimization problem. This is assessed based on a fitness function, and the optimal parameters are obtained as proportional, integral, and derivative gains. Each problem response is evaluated with optimization algorithms to determine the three parameters that yield the best response as the PID index. In this study, the cuckoo, whale, and firefly algorithms are employed. Subsequently, nature-inspired algorithms utilized for PID index optimization are introduced in the following section.

2.2.3. Grey wolf optimization algorithm

The grey wolf optimization algorithm is based on three fundamental behaviors: hunting, ranking, and mating. A pack of wolves interacts with each other to optimize these behaviors. Hunting behavior involves exploring the search space to reach the best position. Grey wolves encircle prey during the hunt. In order to mathematically model encircling behavior, the following equations 24 and 25 are proposed:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_p}(t) - \vec{X}(t)\right| \tag{24}$$

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A}.\vec{D} \tag{25}$$

In the equation t, expresses the current iteration, $\vec{A}$ and $\vec{C}$ coefficient vectors, and $\overrightarrow{X_p}$ position vector of the prey and $\vec{X}$ indicates the position vector of a grey wolf. Vectors are calculated in the below equations 26 and 27:

$$\vec{A} = 2\vec{a}.\overrightarrow{r_1} - \vec{a} \tag{26}$$

$$\vec{C} = 2.\overrightarrow{r_2} \tag{27}$$

Where components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations and $\overrightarrow{r_1}$, $\overrightarrow{r_2}$ are random vectors in [0, 1]. Ranking behavior allows wolves to adjust their positions and strengths relative to each other. On the other hand, mating behavior facilitates the creation of new wolves and the expansion of the solution space. In order to mathematically simulate the hunting behavior of grey wolves, we assume that the alpha (best candidate solution), beta, and delta have better knowledge about the potential location of prey. Therefore, we save the first three best solutions obtained so far and require the other search agents (including the omegas) to update their positions according to the position of the best search agents. The following equations 28, 29 and 30 are proposed in this regard:

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{X}\right|, \overrightarrow{D_\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{X}\right|, \overrightarrow{D_\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{X}\right| \tag{28}$$

$$\overrightarrow{X_1} = \overrightarrow{X_\alpha} - \overrightarrow{A_1}.\left(\overrightarrow{D_\alpha}\right), \overrightarrow{X_2} = \overrightarrow{X_\beta} - \overrightarrow{A_2}.\left(\overrightarrow{D_\beta}\right), \overrightarrow{X_3} = \overrightarrow{X_\delta} - \overrightarrow{A_3}.\left(\overrightarrow{D_\delta}\right) \tag{29}$$

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3} \tag{30}$$

The pseudo-code for GWO is presented in Algorithm 1 (Mirjalili et al., 2014).

2.2.4. Whale optimization algorithm

The whale optimization algorithm operates by maintaining a population of candidate solutions (whales) and iteratively improving them over several generations. In each iteration, the position of each whale is updated using two random vectors, de-noted as A and C, along with a specific formula simulating whale hunting behavior. In order to mathematically model this behavior, the following equations 31 and 32 are proposed:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X^*}(t) - \vec{X}(t)\right| \tag{31}$$

$$\vec{X}(t+1) = \overrightarrow{X^*}(t) - \vec{A}.\vec{D} \tag{32}$$

Where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, X^* is the position vector of the best solution obtained so far, $\vec{X}$ is the position vector. The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows (equations 33 and 34):

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{33}$$

$$\vec{C} = 2.\vec{r} \tag{34}$$

Where $\vec{a}$ is linearly decreased from 2 to 0 over the course of iterations (in both exploration and exploitation phases) and $\vec{r}$ is a random vector in [0,1]. Subsequently, randomness is introduced into the search process by applying a randomization operator to each whale's new position. The fitness value of each whale's new position is computed and compared with the current best position. If the new position is superior to the current best position, it is assigned as the new best position. This process continues until a specific termination criterion is met. The final solution corresponds to the best current position. The detailed steps of WOA are presented in Algorithm 2 (Mirjalili and Lewis, 2016).

2.2.5. Firefly Algorithm

In the firefly algorithm, the disparity in luminosity among fireflies is associated with distance and the density of the environment. This variance delineates the movement of each firefly. The primary objective of the algorithm is to identify the position with the least disparity in luminosity among numerous fireflies. This position nearly represents an optimal solution. Utilizing luminosity differentials as motion vectors, the algorithm establishes a swarm of fireflies navigating within the solution space. Each firefly moves towards the luminosity value of the nearest firefly, thus progressively converging the swarm towards the optimum solution. The proportionality of attractiveness depends on the intensity of light seen by another firefly. Thus, the attractive-ness variation β on r distance is expressed as (equation 35):

$$\beta = \beta_0 e^{-\gamma r^2} \tag{35}$$

Here r equals to 0 and β_0 denotes the attractiveness. Let us assume that there are two fireflies x_i and x_j. Movement of *i*th firefly towards *j*th firefly due to more brightness is defined as (equation 36):

$$x_i^{t+1} = x_i^t + \beta_0 e^{-\gamma r_{ij}^2}\left(x_j^t - x_i^t\right) + \alpha_t \epsilon_i^t \tag{36}$$

Where, the second part of Equation 36 explains the attraction. The third part of Equation 36 is for randomization with α_t. ϵ_i^t defines the vector of random numbers generated by either Gaussian distribution or it can be introduced by uniform distribution with time t. The pseudocode for FA is presented in Algorithm 3 (Kumar and Kumar, 2021).

Algorithm 1. GWO Pseudocode

```
Initialize a population of grey wolves randomly
Evaluate fitness function to determine the fitness value of each wolf
Set alpha, beta, and delta as the three best wolves in the population
while termination criterion is not met do
        for each wolf i in the population do
                Calculate the distance between the current wolf i and alpha, beta, and delta
                Update the position of wolf i
                Apply a randomization operator to the new position of wolf i
                Evaluate the fitness value of the new position of wolf i
                if the new position is better than the position of alpha, beta or delta then
                        if the new position is better than alpha then
                                Set the new position as alpha
                        else if the new position is better than beta then
                                Set the new position as beta
                        else
                                Set the new position as delta
                        end if
                end if
        end for
end while
return alpha
```

Algorithm 2. WOA Pseudocode

```
Initialize a population of whales randomly
Evaluate fitness function to determine the fitness value of each whale
Set the current best position as the position of the whale with the best fitness value
while termination criterion is not met do
        for each wolf i in the population do
        Generate random vector A and C
        if |A| < 0.5 then
            if |C| < 1 then,
                Update the position of whale i towards the current best position
            else
                Update the position of whale i randomly within the search space
            end if
        else
            Update the position of whale i towards a randomly selected whale j
        end if
        Apply a randomization operator to the new position of whale i
        Evaluate the fitness value of the new position of whale i
        if the new position is better than the current best position then
            Set the new position as the current best position
        end if
    end for
end while
return current best position
```

Algorithm 3. FA Pseudocode

```
Initialize a population of fireflies randomly
Evaluate fitness function to determine the fitness value of each firefly
Set the best solution as the current global best
while termination criterion is not met do
for each firefly i do
for each firefly j do
if firefly j is brighter than firefly i then
Compute the distance r_ij between fireflies i and j
Compute the attractiveness β(r_ij) of firefly j towards firefly i
Move firefly i towards firefly j with a step size αβ(r_ij)
end if
end for
Update the global best solution
end while
return the best solution found
```

4. Results and Discussion

In academic studies, the comparative utilization of different approaches is a factor that influences the value of the study. In this study, GWO, WOA, and FA metaheuristic algorithms have been comparatively employed for the purpose of tuning PID controller parameters to minimize error. After modeling the BLDC motor in MATLAB/Simulink, simulations were conducted using different optimization methods for the reference speed value. The MATLAB/Simulink model of the developed BLDC motor speed control system within the scope of this study is presented in Figure 4.

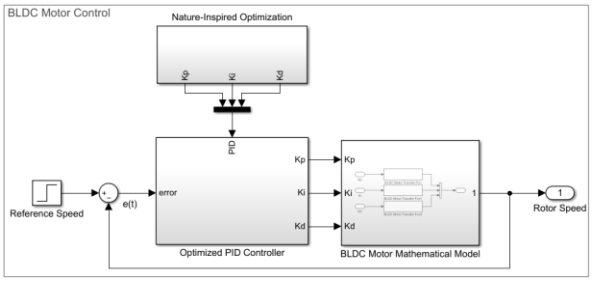

Figure 4. MATLAB / Simulink Model of BLDC Motor Speed Control System.

The population sizes were adjusted to be equal, as the number of individuals in the optimization algorithms affects the simulation results. Common parameters of the optimization algorithms, namely a population size of 50 and a maximum iteration number of 50, were selected. For the accuracy of the results, each optimization algorithm was executed 20 times. The reference value for the output speed (ω) to be used in the simulation was set

to 500 rpm. The range of values for the PID controller parameters is also between [0 - 1]. The graph showing the variation in the fitness value of the optimization algorithms for the specified reference values is presented in Figure 5.

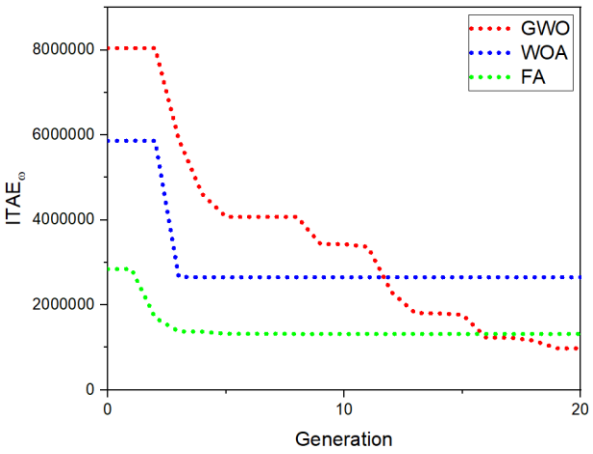

Figure 5. Fitness results.

Furthermore, the ITAE results of each algorithm are presented in Table 2, while the control parameters determined by the optimization algorithms are provided in Table 3.

Table 2. Fitness (ITAE)

Refence Speed	GWO	WOA	FA
500 rpm	977125.99	2654118.29	1320036.50

Table 3. PID parameter in optimization algorithm.

Algorithm	k_p	k_i	k_d
GWO	0.7870	0.0059	0
WOA	0.9699	0.3268	0.0893
FA	0.9241	0.8793	0.0483

Nature-inspired optimization algorithms use stochastic operators. Therefore, the algorithms can produce different results each time they are run. The results in Table 2 were obtained by selecting the best outcomes after running each algorithm 20 times. The optimal outcome was achieved when the speed (ω) control parameter of GWO was evaluated according to the fitness function ITAE. According to the data in Table 2, the results of WOA and FA differ significantly from those of GWO. The disparity be-tween FA in second place and GWO is approximately 35%, whereas the disparity be-tween WOA in third place and GWO is approximately 2.7-fold. The speed (ω) graph obtained using PID parameters determined based on the best outcomes of various optimization algorithms is presented in Figure 6.

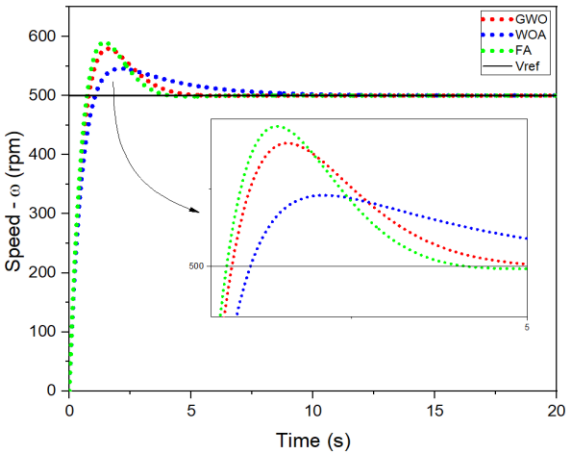

Figure 6. Speed (ω) graphs of BLDC motor. GWO: grey wolf optimizer; WOA: whale optimization algorithm; FA: firefly algorithm.

An optimization algorithm repeats a standard process in each iteration while searching for the optimum value in the solution space. It reaches the optimum value after several iterations. A small number of iterations takes less time, indicating that the algorithm is fast. A speed comparison was made for GWO, WOA, and FA based on the number of iterations required to reach the optimum result. The fastest algorithm is FA, reaching the best result in the 8th iteration. WOA is the second fastest, reaching the best result in the 9th iteration. GWO is the third, reaching the best result in the 19th iteration.

The performance comparisons of optimization algorithms based on the speed graph are provided according to the values of overshoot, settling time, and rise time in Table 4. The minimum overshoot in the speed (ω) response occurs in WOA, while the largest overshoot is observed in FA. According to the data in Table 4, there is an ap-proximate twofold difference between the lowest and highest overshoot values. The overshoot values of GWO are close to those of FA.

The best result in terms of settling time is obtained from FA, whereas the longest settling time is observed in WOA. The difference between the shortest and longest settling times is 91%. The difference between GWO, which ranks second, and FA is 17%. The difference between WOA, which ranks third, and GWO is 63%. In terms of rise time, the best result is obtained from FA, while the longest rise time is observed in WOA. The difference between the shortest and longest rise times is 35%. The difference between GWO, which ranks second, and FA is 9%.

Table 4. Controller performance in the speed parameter (ω)

Algorithm	Overshoot (%)	Settling Time (s)	Rising Time (s)
GWO	15.8585	3.9312	0.5912
WOA	9.1307	6.4128	0.7335
FA	18.0210	3.3566	0.5421

5. Conclusions

In this study, a BLDC motor model with a PID controller was developed and simulated. Controller parameters for the output speed of the developed model were determined using nature-inspired algorithms, namely GWO, WOA, and FA. The performance of these optimization algorithms was compared based on ITAE selected as the fitness function. For the reliability of the obtained results, each algorithm was run 20 times.

According to the data in Table 2, the most successful result in terms of controlling the output speed (ω) was achieved with GWO. GWO was 35% and 2.7-fold more successful than the method that gave the closest and farthest results, respectively. Additionally, controller performances optimized based on overshoot, settling time, and rise time values in the obtained graphs were also examined.

According to the data in Table 4, the best result in terms of overshoot was obtained with WOA. WOA was 1.7-fold and 1.9-fold more successful than the methods that gave the closest and farthest results, respectively. Regarding settling and rise times, the best performances were achieved with FA. In terms of settling and rise times, FA was 17% and 9% more successful than the method that gave the closest results, respectively.

The primary objective of obtaining these controller parameters through optimization methods is to develop an optimal controller without being subject to system limitations. This objective has been achieved as a result of this study. In future research, the comparative use of multi-objective functions and hybrid optimization algorithms is planned for the optimization of control parameters in different types of engines.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	B.E.D.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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Research Article
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ESTIMATING ENERGY NEEDS FOR CLIMATE-CONTROLLED GREENHOUSES IN SYRIA WITH A SOFTWARE TOOL

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Abstract: Amid the current conditions in Syria, the study of energy consumption within plastic greenhouses emerges as a fundamental element in the agricultural economy, especially in areas subject to extreme climate variations. With many thermal power stations ceasing operation due to conflicts and the diminishing sources of energy, understanding energy consumption becomes more urgent to enhance productivity and reduce costs. Successful management of protected agriculture requires in-depth knowledge of weather dynamics and the optimal environmental conditions for crops. To implement effective management of plastic greenhouses, it is essential to recognize how climatic fluctuations affect plant growth and production throughout the various seasons. Heating systems form a significant part of the costs in constructing plastic greenhouses, and deficiencies in these systems can lead to negative impacts on quality, quantity, duration of cultivation, and production volume. Therefore, accurately calculating heating costs is crucial for reducing operational expenses. This study included the development of a computer program to determine the heating needs of plastic greenhouses, considering various factors such as the geographical location of the greenhouse, crop type, covering materials, heating system used, and land area. The results showed that Syria needs 4.56 megawatts of energy for the greenhouses, with the Tartus Governorate consuming the largest share, with energy consumption rates in Tartus, Latakia, Homs, and Damascus countryside amounting to 3.6, 0.3, 0.51, and 0.19 megawatts, respectively. The crops of tomatoes, vegetables, strawberries, and tropical plants consumed 2.2, 1.66, 2.21, and 0.244 megawatts of energy, respectively. This study is an important step towards achieving sustainable and efficient agriculture that contributes to supporting the economy and protecting the environment in Syria.

Keywords: Greenhouse, Heating, Energy, Syria

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1. Introduction

Calculating the capacity of energy in greenhouses in Syria is of paramount importance due to its significant implications for energy management, cost efficiency, and environmental sustainability. As the country faces energy challenges and strives to optimize resource utilization, accurately determining the energy requirements and capacity of greenhouses becomes crucial for effective planning, decision-making, and overall greenhouse performance (Hesenow et al., 2015; Kelley et al., 2015).

Heating is a critical aspect of greenhouse energy management, particularly during the colder months. In Syria's harsh climate, where low temperatures and frost can pose risks to crop growth, providing adequate heating is essential. Calculating the heating capacity involves considering factors such as the greenhouse structure, insulation, outside temperature, desired inside temperature, heat loss, and specific crop requirements (Hainoun et al., 2010). Accurate calculations enable farmers to select appropriate heating systems, optimize energy usage, and minimize costs. Accurate capacity calculations not only aid in optimizing energy use but also have economic and environmental implications. Understanding the energy requirements enables farmers to estimate energy costs, budget effectively, and explore renewable energy options to reduce reliance on fossil fuels. Moreover, efficient energy management in greenhouses contributes to reducing greenhouse gas emissions, promoting environmental sustainability, and aligning with Syria's commitments towards mitigating climate change (Chou et al., 2004).

Ghaly et al. (2024) developed a computer program to calculate the heating requirements for greenhouses in Egypt, based on geographic location, type of product, covering material, type of heating system, and the size of the greenhouse land area. The results showed that the

provinces of Dakahlia and Al-Buhayrah had the highest heating requirements, with values of 37.31 kilowatts for strawberries, 27.8 kilowatts for peppers, 50.89 kilowatts for strawberries, and 40.62 kilowatts for peppers, respectively. (Dimitropoulou et al., 2023) proposed a simple model for predicting the thermal energy requirements of greenhouses in Europe. The model estimates the annual heating requirements and the maximum required heating power, along with the corresponding heating and zero-energy operating periods. It is based on the greenhouse technical data (the overall heat loss coefficient, cover transmission, sensible absorbance), the cultivation conditions (temperature range), and the meteorological data (solar radiation and ambient temperature) according to the site characteristics (longitude and latitude). The results proved that the most significant factor affecting heating requirements, the maximum heating power, and heating periods is the latitude of the greenhouse site, . According to our findings, in lower latitudes (40 to 50 degrees), heating requirements range from 250 to 430 kWh/m^2/y, whereas, in higher latitudes (50 to 60 degrees), heating needs range from 430 to 650 kWh/m^2/y.

(van der Salm et al., 2023) designed a greenhouse for optimal production in the coastal area near Algiers. They evaluated two main options for growing tomatoes and cucumbers: winter production with heating and summer production with air-conditioning and CO_2 injection. The study found that while the production output is similar for both seasons, summer production is more costly by 30%. It also noted that summer production has higher initial investment costs but lower operational costs due to decreased water and energy requirements.

(Morshed et al., 2022) utilized a tubular heat exchanger to heat a greenhouse in the Baniyas region of Syria in a simple, more economical, and environmentally friendly manner. The exchanger pipes, measuring 20 meters in length, were buried at a depth of 1 meter. Two exchangers were established along the length of the plastic greenhouse. The results showed a significant effect of the variables on the heating performance of both exchangers. During the heating period, the soil temperature was between 18 and 19 degrees Celsius, and the average indoor air temperature was between 11 and 12 degrees Celsius. Increasing the pipe length to 20 meters led to an improvement in heating performance by 56%.

(Hainoun et al., 2010) conducted a two-year project to develop an optimal energy supply strategy for Syria, focusing on reducing greenhouse gas emissions and protecting the climate at the lowest cost. The first one deals with the construction of 100 MW wind farm, whereas the second explores the potential of installing about 1.2 million active solar systems for water heating to the year 2030. The result of the first project has shown that the expected annual electricity generation of about 275 GWh leads to a net annual greenhouse gas emission reduction of about 190 kt CO_2 eq corresponding to a cumulative reduction of 3.8 Mt CO_2 during the whole life time of the project. The second project leads to an electricity saving of about 19.33 TWh and depicts a GHG reduction of about 11 M ton of CO_2. (Al Miaari et al., 2023) presents the design and thermal performance evaluation of a novel solar greenhouse with humidification-dehumidification unit, water-cooled heat exchanger and variable mixing ratio in the Mediterranean climate. The greenhouse is designed to provide proper microclimatic conditions for crops, produce fresh water through condensing water vapor released from the plants, and save energy using the semitransparent PV panels. Results showed that on a typical summer day, the solar greenhouse ensures proper microclimatic conditions all day long by reducing the temperature by 11.14 °C compared to conventional greenhouses, while maintaining acceptable values of relative humidity and producing 70 L of fresh water per day.

Attar et al. (2013) stated that the implementation of a flat plate solar collector (FPC) combined with a capillary polypropylene heat exchanger for greenhouse heating in Tunisia resulted in a substantial 51.8% reduction in heating costs for a 1000 m^3 greenhouse during April. Furthermore, this system was found to elevate the internal air temperature of the greenhouse by 5°C. Nonetheless, the accumulated solar energy alone proved insufficient to fully satisfy the heating demands (Attar and Farhat, 2015). It was observed that the influence of reduced temperatures has a significant impact on plant growth, and adjusting the heating temperature set point downward could potentially postpone the initial harvest (Kläring et al., 2015).

In Syria, there are approximately 6,809 hectares of plastic greenhouses. The use of these greenhouse systems serves the purpose of meeting the local market requirements for both vegetables and ornamental plants. In addition to fulfilling local needs, there is an increasing use of polyethylene-made greenhouses for the early cultivation of vegetables, fruits, and flowers in the warm season. Moreover, the production of greenhouses usually surpasses field production in terms of productivity per unit area, consistently delivering higher product quality. Overall, maintaining climate control is of utmost importance in greenhouse agriculture to achieve high crop productivity and high-quality production that meets consumer requirements while ensuring cost-effective production (Khatib and Sizov, 2022).

In this research, the heat balance within a greenhouse can be determined through a comprehensive analysis, which considers various parameters including the greenhouse's geographical location, the type of crops cultivated, the material used for the greenhouse cover, the heating technique employed, and the dimensions of the greenhouse. A computer program has been created, with the expectation that it will offer utility to farmers, agricultural engineers, and individuals interested in these matters.

2. Material and Method

The materials used in greenhouses in the research were regulated according to the thickness of some material's conduction resistances in Table 1. The geographical distribution of greenhouses of Syria in 2022 is given in Table 2. Some meteorological data that can be used in calculating the heating loads of greenhouses that can be established are given in Table 3.

Temperature distribution in degrees Celsius in the regions of Syria is given in Figure 1. Distribution of solar radiation (MJ/m2.day) in Syria shown in Figure 2. The calculation of heating capacities in greenhouses and the flowchart of the program have been developed as shown in Figure 3.

Table. 1 Thermal conduction resistances of some materials used in greenhouses, arranged according to their thickness.

Type of cover material	Thickness (mm)	Thermal conductivity (W/m² c)
Glass	3.18	6.3
A layer of fiberglass	1.02	5.7
Ultraviolet stabilized polyethylene film, PE	0.0003	6.3
Polyethylene film IR absorbing	0.0003	5.7
Polyvinyl fluoride film PVF	0.0008	5.7
Glass-double pane	25.4	3.0
Polycarbonate structured sheets	6.8	3.5

Table 2. The geographical distribution of greenhouses in Syria (2022)*

Location	Varity	Cultivated area (km²)	Production (ton)	Number of Greenhouses
Tartous	Tomato	35.16	300000	82749
	Vegetables	21.03	104000	49476
	Strawberry	2.31	6000	5426
	Tropical Fruit	0.36	0	850
Lattakia	Tomato	2.64	33000	6600
	Vegetables	3.14	19354	7826
	Strawberry	0.03	6	5
	Tropical Fruit	0.32	0	813
Damascus countryside	Tomato	0.004	34	10
	Vegetables	0.35	2612	753
	Strawberry	0	0	0
	Tropical Fruit	0.18	0	438
Homs	Tomato	0.51	4952	1632
	Vegetables	0.14	917	430
	Strawberry	1.7	4728	9493
	Tropical Fruit	0	0	0
Total		67.874	475603	166501

*Ministry of Agriculture and Land Reclamation.

Table 3 Average temperature, wind speed, and solar energy for some Syrian locations:

Location	AT (°C)	AWS (m/s)	SE (MJ/m².day)	SE (kW/m².day)
Tartous	19.36	3.6 m/s	4.826	56.7055
Lattakia	19.4	2.9 m/s	4.481	52.6518
Damascus countryside	18.8	4.3m/s	5.819	68.3733
Homs	17.0	4 m/s	5.462	64.1785

SE= solar energy, AWS= average wind speed, AT= average temperature. Average Temperature and average wind speed data are available: https://unfccc.int/sites/default/files/resource/Syria_Initial%20National%20Communication.pdf. Solar Energy data is available (Global horizontal irradiation is choosed): https://globalsolaratlas.info/map?c=34.375179,37.133789,7&s=34.85889,35.991211&m=site.

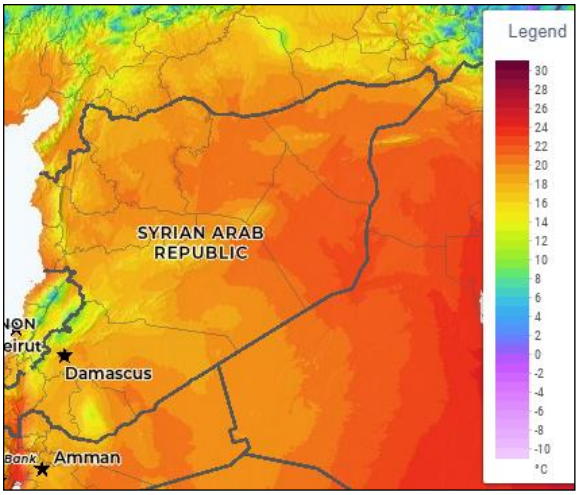

Figure 1. Temperature distribution in degrees Celsius in the regions of Syria

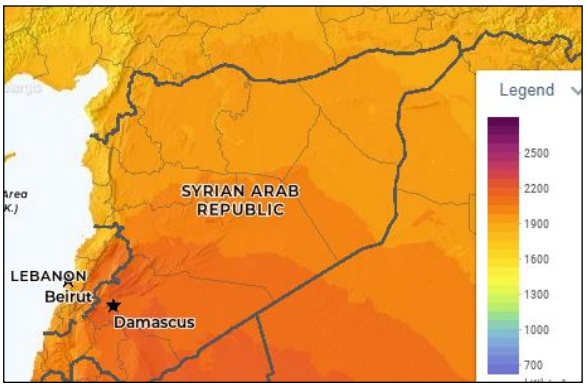

Figure (2) Distribution of solar radiation (MJ/m².day) in Syria

The program adjusts the greenhouse heating capacity as follows: calculations according to equations (Yavuzcan, 1995).

The current requirements for greenhouse heating are determined by assessing the heat losses and gains within the greenhouse, and this calculation is based on the disparity between these factors (equation 1).

$$Q = Q_1 - Q_2 \quad (1)$$

Where:

Q = Greenhouse heat current requirement (W).

Q_1 = Total heat flow lost from the greenhouse (W).

Q_2 = Heat gained from solar energy in the greenhouse (W).

The heat loss from the greenhouse can be quantified using the following equation 2:

$$Q_1 = A * K * (T_i - T_d) \quad (2)$$

Where:

A = Total area of glass or plastic (m²).

K = The coefficient of the total heat transfer (W/m².k).

T_i = Temperature inside the greenhouse (k).

T_d = External temperature (k).

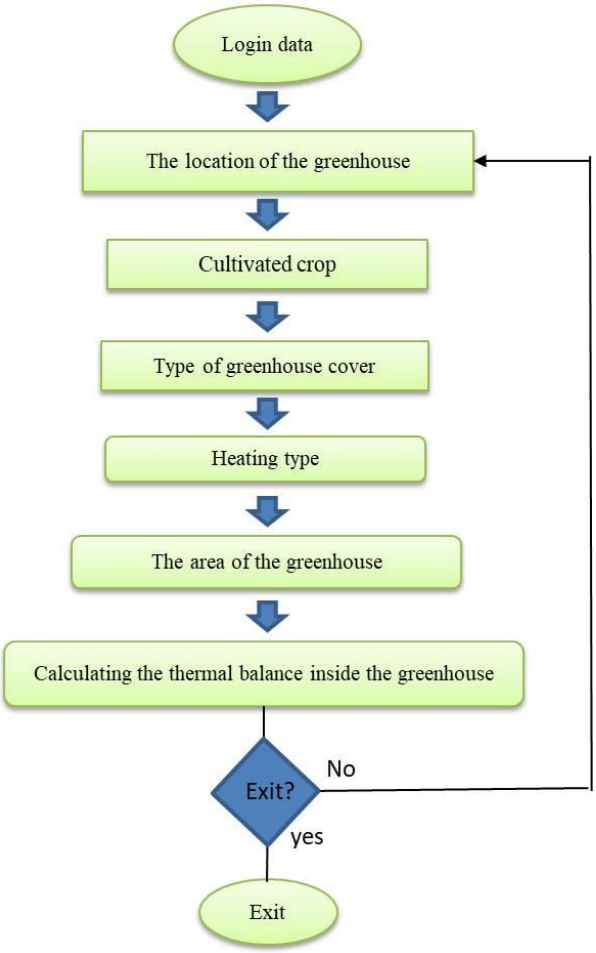

Figure 3. Diagram of the calculation program.

The cumulative heat transfer coefficient from the greenhouse to the atmosphere, encompassing both the total heat transfer and ventilation heat, is the summation of convection coefficients (equations 3, 4 and 5).

$$K = K_1 - K_2 \quad (3)$$

$$K_1 = \frac{1}{\frac{1}{\propto_1} + \frac{d}{\lambda} + \frac{1}{\propto_d}} \quad (4)$$

$$K_2 = 0.19 * v \quad (5)$$

where:

K_1 = Total heat transfer coefficient from the greenhouse to the atmosphere (W/m².K).

K_2 = Heat convection that meets the ventilation temperature coefficient (W/m².K).

α_i = Heat transfer coefficient inside the greenhouse (W/m².K).

d = Thickness of the used cover material (m).

λ= Thermal conduction coefficient of the used cover material (W/m.K).

$\propto_d$= External heat transfer coefficient from the cover surface to the atmosphere (W/m².K).

In Syria, greenhouses commonly employ pneumatic and tubular heaters. Nonetheless, when considering the initial investment and operational expenses, particularly in the context of higher energy costs and central heating

systems, air-type heaters are typically the preferred choice for greenhouse heating (equations 6, 7 and 8).

$$\propto_i = \propto_h + \propto_{t\ddot{o}} \quad (6)$$

$$\propto_{t\ddot{o}} = \frac{Q_{t\ddot{o}}}{A_{t\ddot{o}}(T_i - T_{\ddot{o}i})} \quad (7)$$

$$Q_{t\ddot{o}} = C_t * Q_t * \left[\left(\frac{T_t}{100}\right)^4 - \left(\frac{T_{\ddot{o}i}}{100}\right)^4\right] \quad (8)$$

where:

$\propto_h$= Heat transfer coefficient between hot air and greenhouse air (W/m^2.K).

$\propto_{t\ddot{o}}$= Heat transfer coefficient of the heat carried from the soil to the inner surface of the cover (W/m^2.K).

$Q_{t\ddot{o}}$= Heat flow radiating from the soil to the inner surface of the cover (W).

$A_{t\ddot{o}}$= Greenhouse cover surface area hitting the soil surface (m^2).

$T_{\ddot{o}i}$= Inner surface temperature of the greenhouse cover (K).

C_t= Thermal radiation coefficient of the upper surface of the soil (W/m^{2}K^4).

A_t= Top surface area of soil (m^2).

T_t= Temperature of the upper soil surface (K).

The inner surface temperature of the greenhouse cover can be determined using the following equation 9:

$$T_{\ddot{o}i} = 0.43 * (T_i - T_d) + T_d \quad (9)$$

When calculating the total heat transfer coefficient from the greenhouse to the atmosphere, the convection coefficient for external heat transfer from the cover surface to the atmosphere is determined as follows (equation 10).

$$\propto_d = \propto_{r\ddot{u}} + \propto_{\ddot{o}t} \quad (10)$$

where:

$\propto_{r\ddot{u}}$= External heat transfer coefficient caused by wind (W/m^{2}K).

$\propto_{\ddot{o}t}$= Heat transfer coefficient from the cover surface to the atmosphere (W/m^{2}K).

The amount of heat gained in the greenhouse environment can be calculated from the equation 11:

$$Q_2 = I_0 * A_{\c{c}a} * \eta \quad (11)$$

where:

I_0= Average daily solar radiation intensity (W/m^{2}day).

$A_{\c{c}a}$= The surface area of the greenhouse (m^2).

η= The percentage (%) of solar energy coming to the greenhouse that is converted into useful form in the greenhouse.

The calculation of heating capacities in greenhouses is performed through a computer program developed using MS Visual Basic 6.0 programming language.

3. Results and Discussion

From Table 7, we observe that the Tartus Governorate consumes 86.7% of the thermal capacity for agricultural greenhouses in Syria (Hainoun et al., 2010), due to its extensive cultivation of tomatoes as shown in Table 2, and because tomatoes require higher heat compared to other crops as indicated in Table 4. Following the Tartus Governorate, the Latakia Governorate has consumed 7.45% of the thermal capacity for agricultural greenhouses, then the Rural Damascus Governorate consumes 1.3% of the necessary thermal energy, and the remaining 4.5% is for the Homs Governorate.

From Table 8, we find that tomatoes are the most energy-consuming in Syria, having consumed 53.8% of the thermal energy. This is due to two reasons: the first is the extensive cultivation of tomatoes as shown in Table (2), and the second is the plant's need for high heat compared to other vegetables (Table 4). Vegetables require 40.1% of the thermal energy, strawberries 5.3%, and the rest is for tropical fruits.

From Table 5, in the coastal governorates (Tartus and Latakia), the wind speed is lower than in the inland governorates, and we can also notice a decrease in solar radiation for them (Dimitropoulou et al., 2023).

From Table 1, the use of glass is considered effective in saving energy consumption due to its high thermal insulation, but its high price is one of the main reasons for its limited (Al Miaari et al., 2023).

Table 4. Climate requirements for selected greenhouse crops in hot and arid regions

Crops	Optimal T (c°)		Optimal RH (%)	Reference
	Day	Night		
Tomato	23-27	13-16	50-80	(Ponce et al., 2014)
Vıgıtabels	>24	>14	70-90	(Gruda, 2005) (Kawasaki and Yoneda, 2019)
Strawberry	20-26	13-16	50-65	(Khammayom et al., 2022)
Tropical Fruit	18-24	4-8	70-80	(Max et al., 2009)

Table 5. The total amount of required heat for greenhouses in some regions in Syria

Location	Tartous				Lattakia				Damascus countryside				Homs				Total
Varity	Tomato	Vegetables	Strawberry	Tropical Fruit	Tomato	Vegetables	Strawberry	Tropical Fruit	Tomato	Vegetables	Strawberry	Tropical Fruit	Tomato	Vegetables	Strawberry	Tropical Fruit	--
Q1 (Kw)	3225.003	2125.320	168.952	19.683	207.436	274.582	1.827	13.878	0.592	55.233	0	19.635	67.019	19.743	190.855	0	--
Q2 (Kw)	1156.383	691.659	75.974	11.840	80.620	95.889	0.916	9.772	158	13.879	0	7.138	18.984	5.211	63.280	0	--
Q (Kw)	2068.619	1433.660	92.978	7.843	126.816	178.692	0.911	4.106	0.433	41.353	0	12.497	48.035	14.532	127.575	0	4158.055

Table 7. The required amount of heat for greenhouses by region

Location	Tartous	Lattakia	Damascus countryside	Homs	Total
The required amount of heat (w)	3603100.935	310527.295	54284.4177	190143.096	4158056

Table 8. The required amount of heat for greenhouses by product

Product	Tomato	Vegetables	Strawberry	Tropical Fruit	Total
The required amount of heat (W)	2243904.2	1668239.1	221464.84	24447.64	4158056

4. Conclusion

In Syria, energy consumption in plastic greenhouses is crucial for the agricultural economy, particularly due to climate changes and energy shortages. The study developed a computer program to calculate the heating needs for greenhouses, factoring in location, crop type, and other variables. Syria requires 4.56 megawatts of energy for greenhouses, with Tartus Governorate being the largest consumer at 3.6 megawatts. Tomatoes, vegetables, strawberries, and tropical plants consume 2.2, 1.66, 2.21, and 0.244 megawatts respectively. This research aids in advancing sustainable agriculture in Syria.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	L.G.	G.A.K.G.	B.D.	M. E.
C	40	40	10	10
D	60	20	10	10
S		80	20	
DCP	60	20	10	10
DAI	60	20	10	10
L	40	20	20	20
W	40	20	20	20
CR	50	30	20	
SR	60	20	20	
PM	50	20	20	10
PM	50	20	20	10

C=Concept, D= design, S= supervision, DCP= data collection, and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, PM = funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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BIBLIOMETRIC ANALYSIS OF STUDIES ON CHAT GPT WITH VOSVIEWER

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Abstract: Chat GPT, which suddenly entered our lives at the end of 2022, is a large language model and has attracted the attention of people from all walks of life. Following this, researchers have also conducted studies in many areas related to Chat-GPT in the literature. For this purpose, bibliometric data of different types of works scanned in the Web of Science database and published between 2020-2024 was taken as basis. When we look at the distribution of 415 works related to Chat GPT according to publication years, it is seen that the most were produced in 2024 (222 works), 2023 (186 works) and in each of other years (2 works). It is seen that there has been a concentration in the last two years; the authors who produced the most works are Viroj Wiwanitkit, and Wisit Cheungpasitporn and Jerome R. Lechien; The publication type is mainly journal article (286), paper (48), early appearance (45), review article (30) and letter(6); When the top five research fields are examined, it is found that works are published in the fields of computer science (101), general medicine (50), educational research (32), and surgery (26); the leadership in the distribution of publications by country is with publishers from the USA (123), China (47), and India (33); works are published primarily in English (405), Spanish (6), and Portuguese (3); and publications scanned in SCI-E (227), ESCI (115), and SSCI (45) indexes predominate. When the most frequently used keywords in publications related to Chat GPT are examined, the following are the leading expressions: “artificial intelligence” with 101 occurrences, “Chat gpt” with 90 occurrences, “large language models” with 43 occurrences, “chat gpt” with 42 occurrences, “ai” with 29 occurrences, “chat-gpt” with 27 occurrences, and “chatbot” with 17 occurrences.

Keywords: Chat GPT, Artificial Intelligence, AI, LLM, Chatbot

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1. Introduction

Chat GPT is a generative artificial intelligence tool from the large language model family developed by OpenAI. Generative artificial intelligence is a complex artificial intelligence system that can understand, produce and transform human language thanks to advanced machine learning techniques such as deep learning and neural networks (Bulut, 2024). Using the generative artificial intelligence model; texts can be produced as if they were produced by humans. Not only text production; but also, digital content production including visuals, audio, coding and natural language can be carried out using AI models (Cao et al., 2023).

Table 1 shows the versions and pricing of Chat GPT from the time it was popular to the present day. While GPT-3.5 has 175 billion parameters, GPT-4 is said to have 1.7 trillion parameters. Parameters are settings that allow fine-tuning of the content in AI responses, including tone, style, and creativity. GPT 3.5 can process up to 3,000 words, Chat GPT-4 can process up to 25,000 words, and GPT-4 Turbo can process up to 96,000 words (Meer, 2024). Chat GPT Plus, offered for a monthly subscription fee of $ 20, provides its users with additional benefits such as priority access and internet search (Bulut, 2023). On May 14, 2024, a completely new version, GPT-4o, was introduced and it was mentioned that it was equipped with more human features (Bulut, 2024). It is currently available free of charge for limited use.

The free version of Chat GPT is GPT-3.5, and the paid version, Chat GPT Plus, is based on GPT-4 technology. It is known that the data for both versions of the training dataset was received until September 2021. This can sometimes cause difficulties in achieving the desired results. In general, it is stated by the authorities that the Plus version is ten times better than the GPT 3.5 version. However, due to its free nature, 30% of Chat GPT users still prefer GPT-3.5 (Subham, 2024).

According to the latest data, Chat GPT has 100 million weekly active users and over 180.5 million monthly users as of August 2024. Daily traffic to Chat GPT has exceeded 100 million visits after the announcement of GPT-4o. It took only 5 days for Chat GPT to add 1 million users after its launch. Based on this active data, using Chat GPT versions in studies seems like an inevitable result (Meer, 2024).

Table 1. GPT versions and release dates (created by the author)

Version Name	Release Date	Fee
GPT 3.5	November 30, 2022	Free
GPT-4	March 13, 2023	Paid
GPT-4 Turbo	November 6, 2023	Paid
GPT-4o	May 13, 2024	Paid/Limited use
GPT-4o mini	July 18, 2024	Paid/Limited use

1.2. Literature Review

Bibliometric analysis on Chat GPT has been studied by many people and in different fields in 2024. The fact that it is a popular topic, and people are working on it means that more publications will be produced on Chat GPT.

Baber et al., in their 2024 study, examined in depth 34 of the 328 publications retrieved from the Scopus database. They stated that GPT studies were in the early stages since the data for this study was retrieved in 2023; they said that applications such as natural language processing and understanding, dialogue systems, speech processing and recognition, learning systems, chatbots and response generation were emphasized. The USA is at the forefront in publishing and new keywords on this subject. The emerging themes are: "patient care", "medical", "higher education" (Baber et al., 2024).

Tian et al. (2023) conducted a bibliometric analysis on ChatGPT through Web of Science in 2023. In this study, a total of 206 articles were examined between 2020 and 2023. The keyword analysis found that chatbot was the main keyword. It revealed that national collaborations were made in America, China and Australia (Tian et al., 2023).

Kurnianingrum et al. conducted an analysis using the Scopus database in their 2024 study. Data were extracted in ChatGPT and English. In the first stage, topic analysis LDA (Latent Dirichlet Allocation) was used for the dataset of publications with related topics to understand the structure of citations and publications. Then, bibliometric analysis was performed using VOSviewer software. Of the 55 articles obtained, 49 were published in journals, and the remaining 6 were published in seminar proceedings. All of these articles were published in 2023 and have a total of 169 citations. "Artificial Intelligence" is the most repeated keyword, followed by "ChatGPT", "human" and "people" (Kurnianingrum et al., 2024).

In their study in 2024, Safdar et al. conducted bibliometric analysis using the Scopus database using applications such as Biblioshiny, VOSviever, Python, MS Access and Excel and Endnote. It was determined that European countries such as the USA, England and Germany led the way, but the USA ranked first with 90 publications and 1,720 citations in this context (Safdar et al., 2024).

García-Carreño conducted an analysis of studies conducted on ChatGPT in social sciences in 2024. Focus was placed on 220 articles out of 828 from the Scopus database. Analysis was conducted with Voswiever. References were transferred to Mendeley and Prisma was used for meta-analysis. While there were 217 studies in 2023, this number decreased to 3 in 2024. He reported that the most studies were conducted in the USA (57), England (23) and Australia (17). He said that the keywords were “Chat GPT”, “ai” and “chatbot” (Carreño, 2024).

Oliński focused on 814 articles from the Scopus database for studies in social sciences in 2024. As a result of the analysis made with VOSviewer; it is seen that the USA, China and England are the countries with the most publications, and when the keywords are examined, the words “Chat GPT”, “student” and “technology” stand out (Oliński et al, 2024).

Apart from these studies, there are also studies on ChatGPT in different fields: Khosravi et al. (2024) on Chatbot and GPT topics; Barrington et al. (2023) in medical studies; Zheltukhina et al. (2024); Liu et al. (2024); Samala, et al. (2024); Polat et al. (2024) in education; Khan et al. (2024) in multi-disciplines; Farhat et al. (2024) conducted bibliometric studies investigating the early footprints of Chat GPT.

2. Materials and Methods

In the study, bibliometric analysis was conducted with information extracted from the WOS database on the topic of "Chat GPT". Bibliometric analysis is a tool used for mapping and evaluating scientific knowledge. This method collects data from publications such as scientific journals, articles, and citations, and then analyzes the data to find relevant patterns (Nandiyanto et al., 2021; Kazak and Kazak, 2023; Kumar et al., 2024; Nandiyanto et al. 2024; Buele and Guerra, 2021). Many studies have been conducted in the field of computer science using VOSviewer (Gandasari et al., 2024; Kumar et al., 2024; Ninova and Ninov, 2024; Ria, 2024; Darmawan et al., 2024; Li, 2024; Khong et al., 2024; Fahrudin,2024; Kumari et al., 2024).

The latest version of the VOSviewer program, version 1.6.20, was used for the analysis. Search results in the WOS database can be easily transferred to the VOSviever software via the interface. The information retrieved from the WOS page was downloaded to the computer in txt format. The transferred format includes the publication year, language, journal, title, author, organization, keywords, document type, abstract and number of citations. This information was accessed on September 3, 2024, the date of the analysis.

In the light of the information obtained from the query

made in the WOS database with the keyword Chat GPT, answers to the following questions were sought:

RQ1. What are the basic information and number of the publications on ChatGPT?

RQ2. Who are the authors who conducted Co-Author Analysis on ChatGPT?

RQ3: How is the Citation Analysis of Authors publishing on Chat GPT?

RQ4: What is the Citation Analysis of Countries publishing on Chat GPT?

RQ5: How is the Citation Analysis of Countries that publish on Chat GPT?

RQ6: How is the Citation Analysis of Institutions that publish on Chat GPT?

RQ7: How is the Keyword Analysis of publications on Chat GPT?

RQ8: How is the Bibliographic Matching Analysis of Texts of publications on Chat GPT?

RQ9: What is the Bibliographic Match Analysis of Authors who published on Chat GPT?

RQ10: How is the Co-Citation Analysis of the Authors who published on Chat GPT?

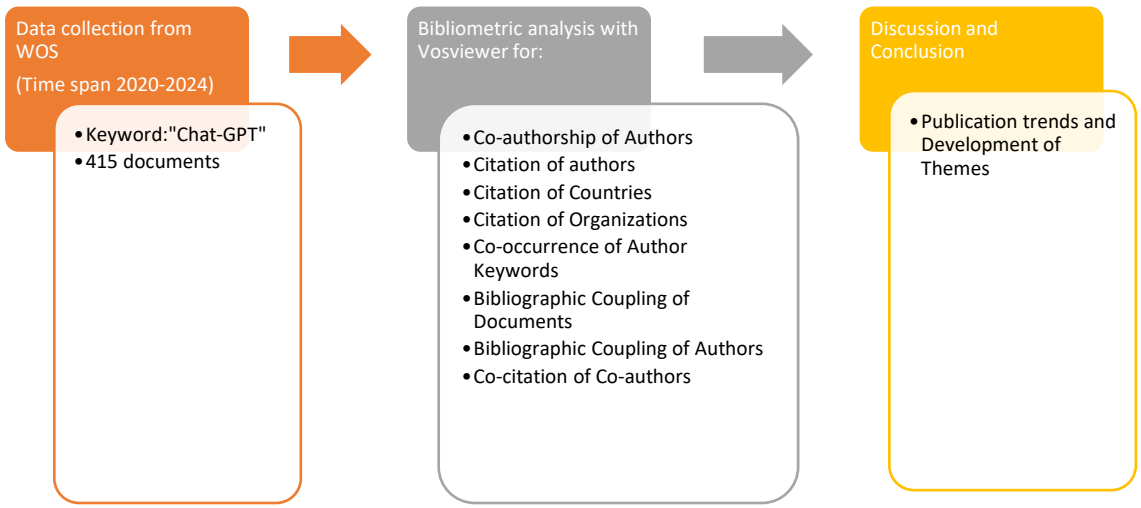

Figure 1. Bibliometric analysis stages.

Figure 1 shows the stages of the bibliometric analysis. In the first stage, data were extracted from the WOS database, in the second stage, it was loaded into the analysis program Vosviever and the previously determined analyses were performed. In the last stage, trends and themes were determined and discussion and conclusion sections were created. Each question is analyzed as a sub-heading.

3. Results

Analyses were made for the previously determined questions and results were obtained.

3.1. Basic Information and number of publications

Some of the basic information obtained because of the query in the WOS database is shown in Figure 2.

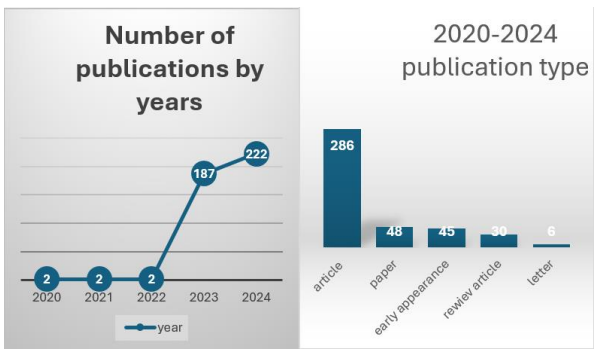

Figure 2. Number and type of publications.

Figure 2 shows the number of publications obtained according to the Chat GPT keyword according to years. Since 2022, the year we started to hear the name of Chat GPT, there has been a sudden increase in the number of publications, which was 187 in 2023, while this number was 222 in the current year. In general, when we look at the types of publications, it was determined that the most common type of publication was articles with 286, papers 48, early views 45 reviews 30 and letters 6. When we look at the types of publications, we see that SCI-E 227, ESCI 115, SSCI 45, Conference proceedings CPCI 21, A&HCI 7. When we look at the first five countries in which authors from which countries have made publications; USA comes with 123 publications, China 47, India 33, Germany 31, Italy 26. There are 13 publications from Türkiye.

When we look at the top five in the subject distribution of the general WOS index, 101 publications in the field of computer sciences, 50 in the field of general medicine, 32 in educational research, 26 in surgery and 25 publications related to the method of computer science theory. From this point of view, we can say that the subjects are generally concentrated in the fields of computer sciences, education and health. When we look at the authors with the most publications, the top five are Wiwanitkit V. 5, Cheungpasitporn W. 5, Lechien, J. R. 4, Thongprayoon, C. 4, Georgakopoulou, V. E. 4. Chat GPT, identified as an author, also has 2 publications. Öztürk A., a Turkish author, also has 2 publications.

3.2. Co-authorship of Authors

By setting a minimum criterion of one publication and one citation, a network map was constructed to identify the authors with the most significant connections and collaborative efforts. The analysis revealed that 17 authors, identified as the most interconnected, were grouped into a single cluster, with a total of 136 connections observed.

As depicted in Figure 3, the author with the highest number of connections within the clusters is Lechien J., who has 4 publications and 52 citations. Following him are M. Mayo-Yanez with 3 publications and 44 citations, and A. Maniaci with 3 publications and 13 citations. The most frequently cited authors include Biswas Som with 257 citations and six others, each with 163 citations

3.3. Citation Analysis of Authors

A network map for author citation analysis was constructed using criteria of at least one publication and one citation, with the aim of identifying citation networks. The analysis of 241 interconnected units revealed a total of 13 clusters, 1,367 connections, and an overall connection strength of 1,492.

As shown in Figure 4, Biswas S. has the highest degree of linkage, with 2 publications and 257 citations. He is followed by Lechien J., who has 4 publications and 52 citations, and Cammarato G., who has 3 publications and 51 citations.

3.4. Citation Analysis of Countries

A network map was generated to analyze the citations received by publications based on their countries of origin. This analysis focused on 50 interconnected observation units, using the criteria of at least one publication and one citation per country. The results identified 9 clusters, 251 connections, and a total connection strength of 392.

As depicted in Figure 5, the countries with the highest citation counts are the USA (958 citations), China (431 citations), and Australia (357 citations). These countries also rank in the top three in terms of total link strength. Regarding the number of publications, the USA leads with 123, followed by China with 47, and India with 33.

3.5. Citation Analysis of Organizations

A network map of inter-institutional citations was created by analyzing 164 interconnected observation units, based on the criterion of at least one publication and one citation per institution.

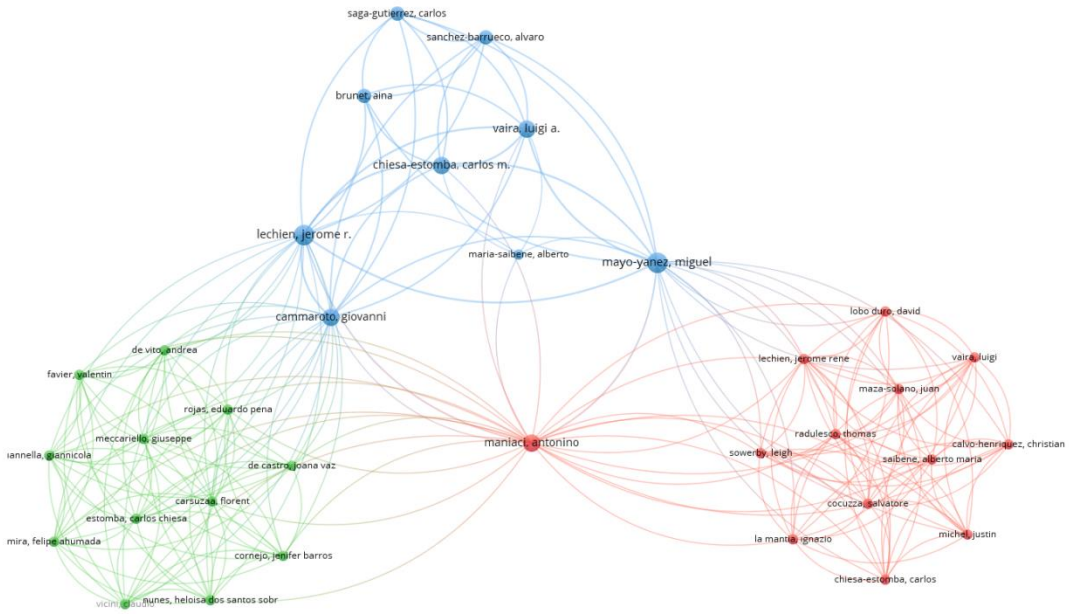

Figure 3. Co-authorship of authors.

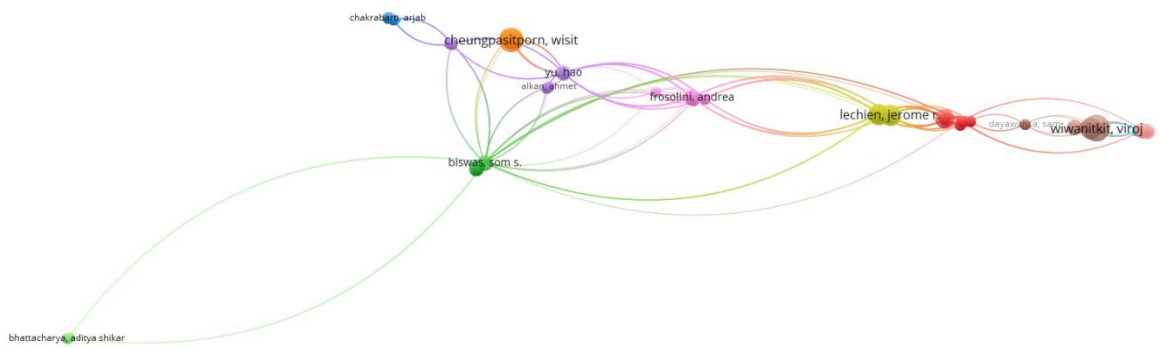

Figure 4. Citation analysis of authors.

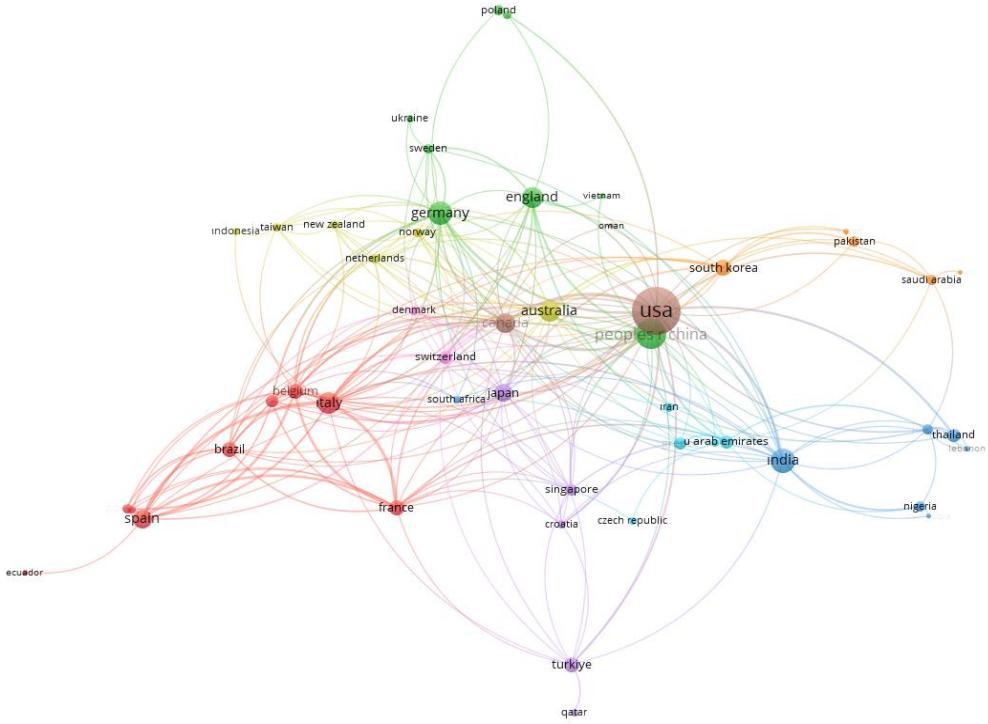

Figure 5. Citation analysis of countries.

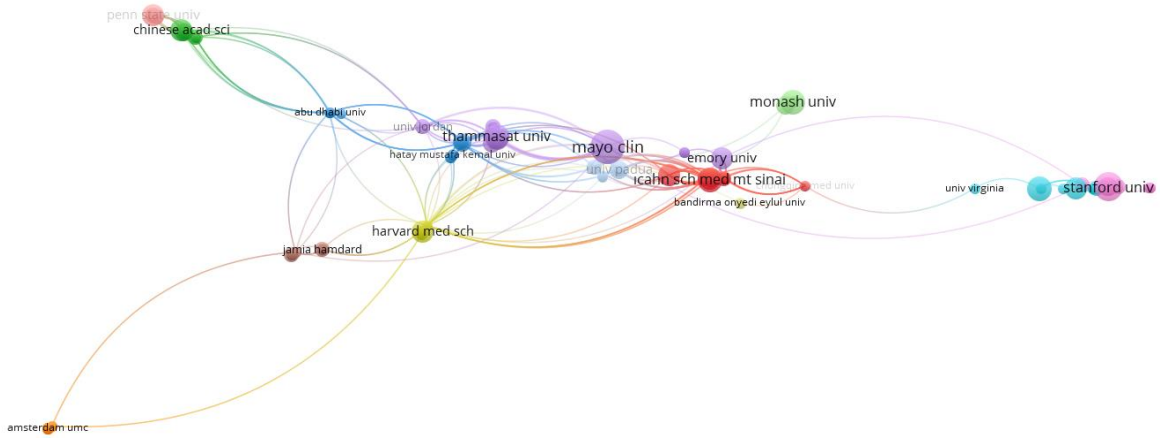

Figure 6. Citation analysis of organizations.

As illustrated in Figure 6, Mayo Clinic (10 publications), Stanford University (7 publications), and Thammasat University (5 publications) are among the most represented institutions by the number of works. The institutions with the most cited publications are the University of Tennessee (182 citations), Chinese Academy of Sciences (170 citations), and Chinese Academy of Sciences University (165 citations). The analysis revealed 13 clusters, 703 connections, and a total connection strength of 746.

3.5. Keyword Analysis (Co-occurence of Author Keywords)

An analysis of 69 observation units, each appearing at least three times and demonstrating interconnections, identified 9 clusters, 520 connections, and a total connection strength of 999.

As illustrated in Figure 7, in publications related to ChatGPT, the most frequently used keywords include 'artificial intelligence,' leading with 101 occurrences, followed by 'ChatGPT' with 90 occurrences, 'large language models' with 43 occurrences, 'chat gpt' with 42 occurrences, and 'AI' with 29 occurrences. The phrases with the highest total connection strength were 'ChatGPT,' 'artificial intelligence,' 'large language models,' 'chatbot,' and 'chat-gpt'.

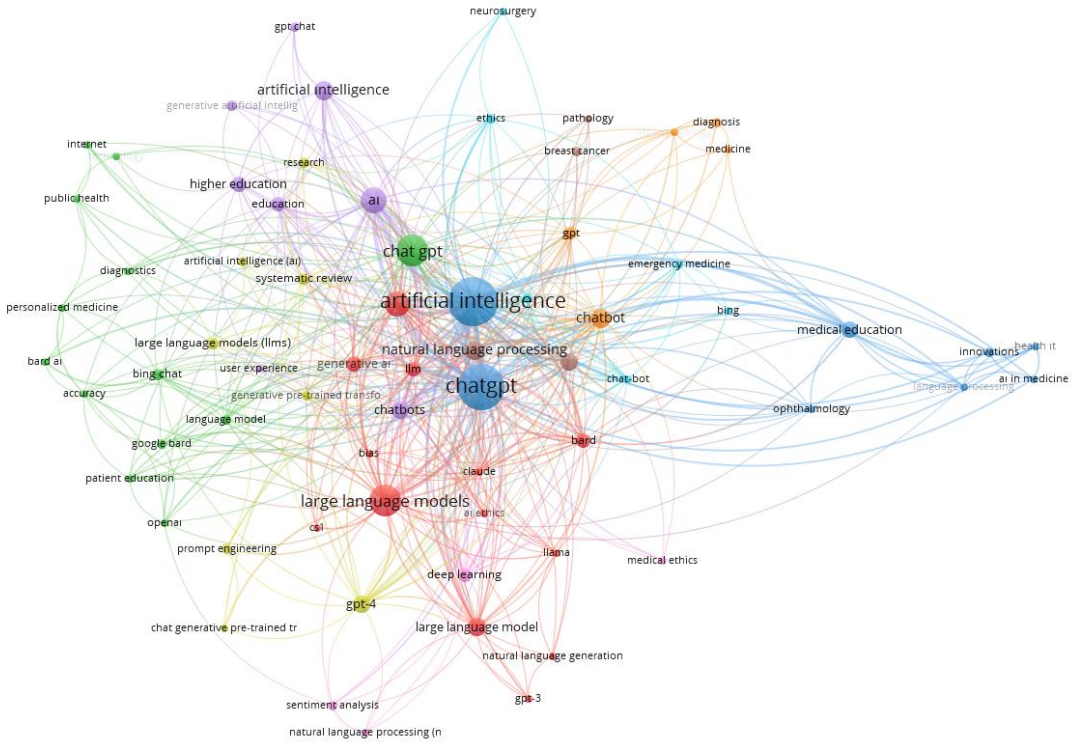

Figure 7. Keyword analysis (Co-occurence of author keywords).

An important point that draws attention is that since a standard spelling is not preferred for the words chat gpt and chat gpt, these two keywords have produced results as if they were different words. There is even a keyword in the form of Gptchat. However, the words are the same even if they are written differently. In fact, with 132 repetitions, which is the sum of the two words, it repeated more than the keyword artificial intelligence.

3.6. Bibliographic Coupling Analysis of Documents

Bibliographic matching occurs when two independent sources cite a common work. An analysis of 171 works, selected based on the criteria of having at least one citation and an interconnection, identified 11 clusters, 2,280 connections, and a total connection strength of 3,435.

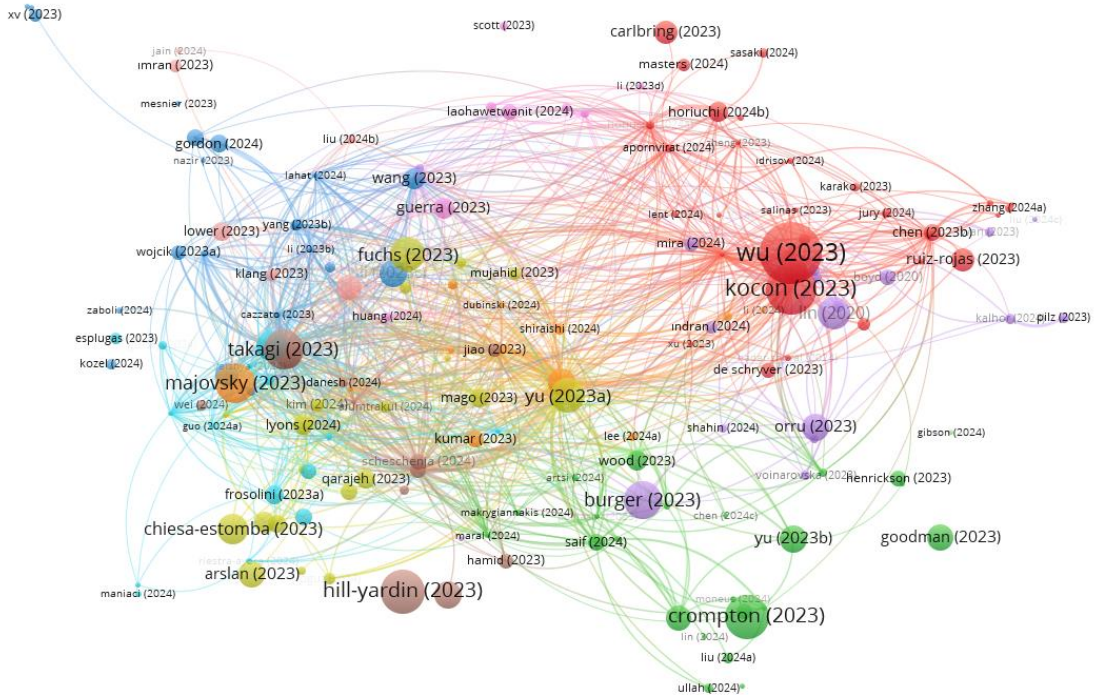

Figure 8. Bibliographic coupling analysis of documents.

As shown in Figure 8, the publications with the highest number of bibliographic matches are Biswas (2023a) with 182 citations, Wu (2023) with 163 citations, and Kocon (2023) with 108 citations. The works with the highest total link strength are Sohail (2023), Jefferson (2018), and Watters (2023).

3.7. Bibliographic Coupling Analysis of Authors

Using the criterion of having at least one published work, one citation, and an interconnection, an analysis was conducted on 871 units. The results revealed 21 clusters, 76,092 connections, and a total connection strength of 240,447."

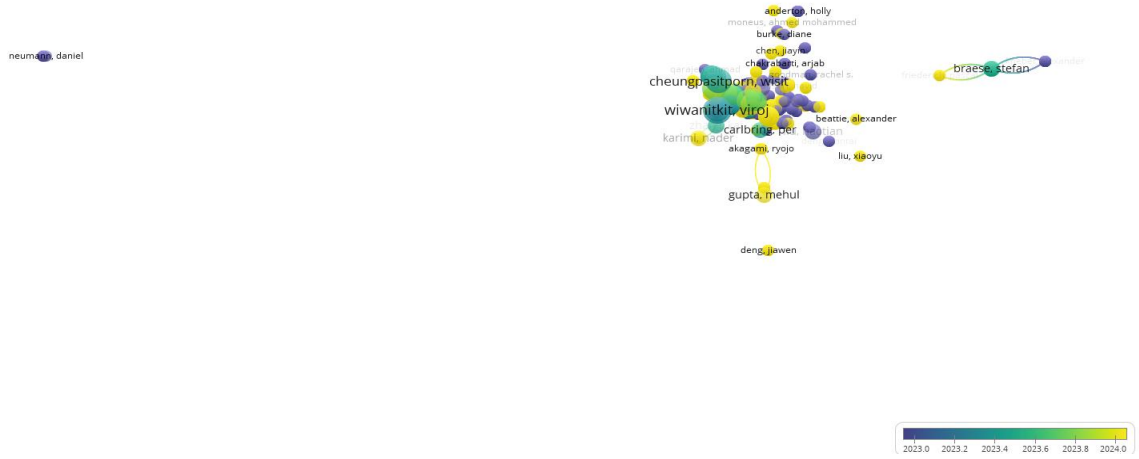

Figure 9. Bibliographic coupling analysis of authors.

As depicted in Figure 9, the authors with the highest number of bibliographic matches are Som S. Biswas with 257 citations (0 link strength), Qing-Long Han with 163 citations (1,814 link strength), and He Shizhu with 163 citations (1,814 link strength).

3.8. Co-citation of Co-authors

Co-citations refer to different sources cited together in a publication. An analysis was conducted on 45 units, selected with a minimum of 10 citations. The analysis identified 5 clusters, 570 connections, and a total connection strength of 2,165.

As shown in Figure 10, the most commonly cited authors were OpenAI (86 citations), Tiffany Kung (33 citations), and B. Brown (30 citations).

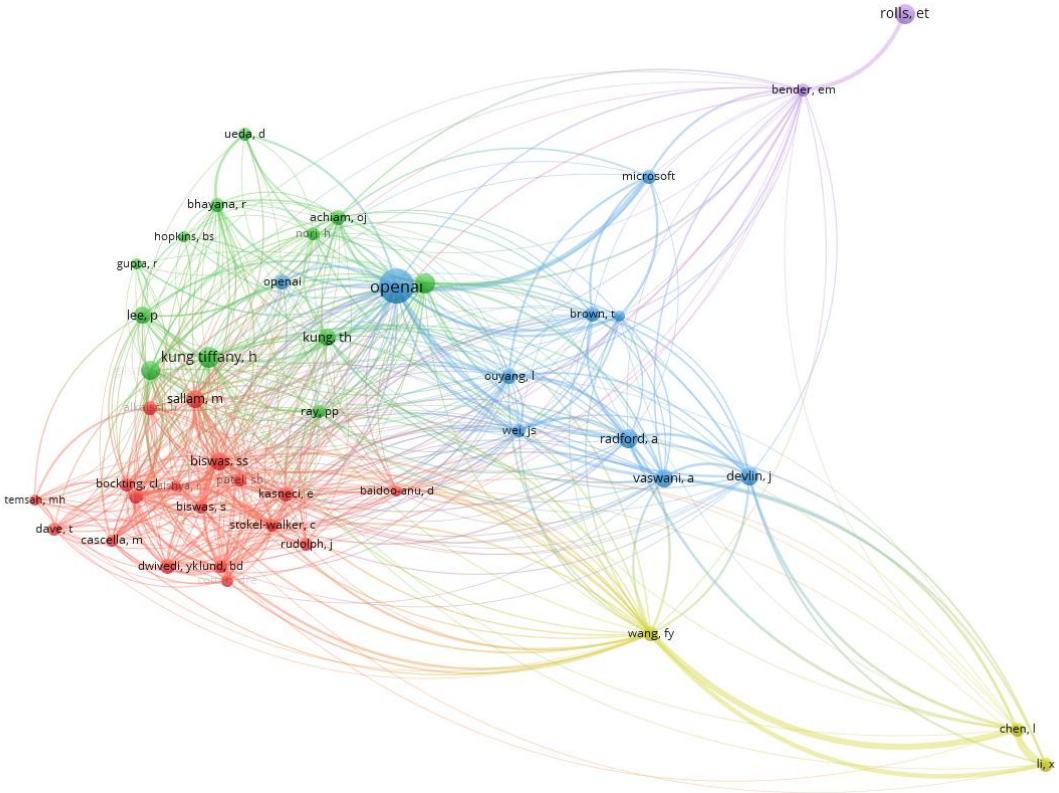

Figure 10. Co-citation analysis of co-authors.

4. Discussion and Conclusion

The publications related to Chat GPT were taken from the WOS database and the data were analyzed objectively and comprehensively. The research conducted consists almost entirely of articles published in English. The small number of articles written in other languages and the small total sample size prevented the use of language restrictions. It is inevitable that most of the publications are in the fields of artificial intelligence, information systems and multidisciplinary applications in computer science. It also shows that Chat GPT is used in the fields of medicine and education.

416 publications about Chat GPT indexed in the WOS database were included in the analysis. It was determined that the most frequently used keywords were "artificial intelligence" and "Chat gpt". When looking at other keywords, it was observed that there were new combinations of the word Chat GPT written with different notations. A single usage type was not adopted, and authors used different methods when writing keywords. When we examine the keywords in the Keyword Analysis, the words 'Google Bard', 'Bingchat' are also seen in some studies. Google Bard is also an LLM model, and its name was changed, now it is Gemini (Rayhan, 2024). Similarly, Bing has changed its name and is called Microsoft Copilot (Microsoft, 2024). In many studies, they are used with Chat GPT for comparison performance in different domains (Rudolph et al, 2023; Afgiansyah, 2023; Dao, 2023; Motlagh et al, 2023; Giannakopoulos et al, 2023; Sallam et al, 2024; Krause, 2023; Makrygiannakis et al, 2024).

When we look at the co-authorship of the authors; If we take the release year of Chat GPT as 2022, it is a subject of about 2 years, so the authors mentioned do not have many publications. When we look at the distributions based on years, the number was 2 in 2022, 186 in 2023 and 222 in 2024. However, since this topic is open-ended and can be used in connection with every field, there is no doubt that the numbers will increase. It is seen that America is both the most cited and the most published country. China comes next.

Another important point is that when we look at the authors, we see that the most cited author is Openai. This shows that researchers get information from Openai as a primary source with Chat GPT. At the same time, Chat GPT is now shown as the author in the studies. It can be labeled as a co-author or a partial author. It can be given as an author in the sources section as "OpenAI. (2021). ChatGPT (Version 3.5) [Software]. Retrieved from https://openai.com/". In the authors section, GPT C. and 'Artificial Intelligence, OpenAI, San Francisco, CA USA' can be given as author addresses. As an example of author attribution, there are two studies in this analysis in which Chat GPT was added as an author (Matusov et al, 2023; Sampath et al, 2023). However, no one is responsible for the accuracy of the content produced by Chat GPT. It is left entirely to the user to investigate the accuracy of the content produced here. In fact, Chat GPT now warns "ChatGPT may make mistakes. Check important information." warning message.

When we analyse the keywords given by the authors in more detail; the word 'ethics' also draws attention. Ethics is one of the biggest problems when it comes to Chat GPT. For example, with the increasing number of people using Chat GPT to create original-like text content without citation, the copyright of the content created by ChatGPT is becoming a serious concern (Wu et al., 2024). In addition, the use of Chat GPT brings ethical issues such as potential security, confidentiality, toxicity, bias and plagiarism. (Hua et al., 2024). Nevertheless, there are some guidelines for researchers to benefit from Chat GPT in their publications. In our country, the Council of Higher Education has published a guide describing how artificial intelligence can be used in publications (YÖK, 2024). A Guide to Productive Artificial Intelligence has been prepared by UNESCO to show how it can be used in Education and Research in line with the 2030 Sustainable development goals (Unesco, 2024). There is another guide published by the European Union Commission for the responsible use of productive artificial intelligence in research (European Commission, 2024).

When we look at the limitations of the study; using only the WOS database, not making use of other large databases, the fact that the subject has been actively studied for only 2 years, the authors not using a uniform method in keyword tagging but naming it differently are the first things that come to mind. Publications on Chat GPT have also been made in databases such as Scopus, Google Scholar, Pubmed, IEEE, Researchgate. In the light of the data obtained from these databases in different studies, biometric analysis can be performed with a different tool such as Biblioshiny. Vosviewer tool was used for visualisation; however, tools such as Bib Excel, Publish or Perish, Gephi and HistCite can also be preferred.

When the importance and benefits of Chat GPT in human life are evaluated; to evaluate and guide the studies to be conducted on the subject, a bibliometric analysis was conducted on the articles containing the word "Chat-GPT" in the Web of Science database until September 3, 2024. As a result of the findings of the research, it is important to contribute to the development of the subject by conducting studies in the fields of education, health, user experience for NLP natural language processing in the literature.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	S.B.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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SYNTHESIS OF HETARYL SUBSTITUTED PYRAZOLO[3,4-*b*]QUINOLINONE SYSTEMS BY MULTICOMPONENT CYCLOCONDENSATION REACTION

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Abstract: In this study, the synthesis of pyrazolo[3,4-*b*]quinolinone compounds was carried out via one-pot three-component reactions. These reactions proceed as domino processes, making them easier to occur than the conventional multistep organic reactions. By employing this method, new organic molecules can be synthesized in a single step, using minimal time and number of trials. In the first phase of this two-step study, heteroaromatic carbaldehydes (quinoline-8-carboxaldehyde and quinoline-4-carboxaldehyde) were prepared to be used as substrates in subsequent reactions by oxidation of 8-methylquinoline and 4-methylquinoline with selenium dioxide, a mild oxidant. In the second step, heteroaromatic carbaldehyde reacted with aminopyrazole and dimedone in anhydrous ethanol by one-pot multicomponent condensation method to synthesize six compounds with heteryl-substituted pyrazolo[3,4-*b*]quinolinone ring system. The crude products were obtained in excellent yields and further purified by crystallization. The structures of the compounds, which were found to be completely pure as a result of chromatographic studies, were elucidated by spectroscopic methods and elemental analysis.

Keywords: One-Pot reactions, Quinolinone, Selenium dioxide, Methylquinoline, Multicomponent reactions (MCRs), Biological activity

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1. Introduction

Presently, chemical research is preponderantly focused on synthesizing new compounds that potentially have biological activity and measuring this activity. Heterocyclic systems and their substituted derivatives, which are among the most important classes of organic chemistry, are widely used in medicine as well as in industry (Desenko et al., 2024; Doğan et al., 2022; Gümüş et al., 2024). Multicomponent reactions take place when three or more starting materials react in a reaction vessel to form a target product containing portions of all the initial materials (Zhu and Bienayme, 2005). It is well known that heterocyclic compounds are generally formed by intramolecular or intermolecular cyclization reactions (cyclocondensation) of straight-chain substances (Gümüş et al., 2018).

In previous research concerning the preparation of quinolinone rings, they were synthesized via one-pot three-component reactions using dimedone and benzaldehyde derivatives with aminopyrazole derivatives (Quiroga et al., 1998a; Quiroga et al., 2001; Danel et al., 2022), aminopyrimidine derivatives (Quiroga et al., 1998b), and aminobenzimidazole derivatives (Lipson et al., 2003a; Chebanov et al., 2010), and pyrazolo[3,4-*b*]quinolinone ring system was investigated as inhibitors of glycogen synthase kinase 3 with exquisite kinomewide selectivity and their functional effects (Wagner et al. 2016).

Furthermore, it was observed that mostly the phenyl group and its derivatives were found in the quinolinone systems since benzaldehyde and its derivatives were used as substituents. In light of this information, this study aimed to synthesize new heteryl-substituted quinolinone derivatives by multicomponent cyclocondensation reaction technique.

In the first step, heteroaromatic carbaldehydes were synthesized by oxidation of methylquinolines with selenium dioxide, which is a weak oxidant (Kaplan, 1941; Seyhan and Fernelius, 1957). In the second step, heteroaromatic carbaldehyde reacted with corresponding aminopyrazole and dimedone in anhydrous ethanol by one-pot multicomponent condensation method to synthesize six compounds with heteryl-substituted pyrazolo[3,4-*b*]quinolinone ring system.

2. Materials and Methods

2.1. Equipment and Supplies

Fourier Transform Infrared (FTIR) spectra of the products were obtained on a Perkin Emler Spectrum One FTIR spectrophotometer by tableting with potassium bromide. Nuclear magnetic resonance (^{1}H NMR and ^{13}C NMR) spectra were obtained in DMSO-d_6 (using tetramethylsilane (TMS) standard) on a Varian Mercury 400 MHz spectrophotometer. Mass spectra were obtained using a Hewlett Packard GC/MS 6890/5973 70 eV spectrometer. Elemental analysis was performed using a Thermo Electron Corporation, CHNS-O Analyzer.

Solvent recovery during extraction and crystallization of the products was performed in a Heidolph VV 2000 rotary evaporator. In thin layer chromatography (TLC), "Merck silica gel 60 F254 aluminum layer" with fluorescent indicator and "Desega Min UVIS, 50 Hz UVP" 254 nm ultraviolet lamp were used. The melting points of the isolated pure substances were determined in a "Gallenkamp" model melting point apparatus with open capillary tubes and no thermometer correction was made.

2.2. Preparation of Selenium dioxide for use as an Oxidant in the Preparation of Carbaldehydes

Selenium dioxide was prepared by oxidation of metallic selenium with nitric acid or by combustion in oxygen and nitrogen dioxide. Purification can be performed by crystallization or sublimation; however, sublimation is preferable. Since selenium dioxide and selenious acid are very expensive substances, it is important to recover metallic selenium. The recovered metallic selenium was pulverized, washed with suitable solvents to remove organic impurities, and then dried so that it can be reused. While concentrated nitric acid (20 g, 14.1 mL) in a porcelain capsule was heated in a fume hood and burner flame, metallic selenium (10 g) was slowly added in portions. The resulting solution was heated at a temperature not exceeding 200 °C until the selenous acid was completely evaporated. The crude product was purified by sublimation (Blatt, 1986).

2.3. Preparation and Properties of Hetaryl Substituted Carbaldehydes

2.3.1. Synthesis of quinoline-4-carboxaldehyde

After adding selenium dioxide to the solution of 4-methylquinoline in dioxane, the reaction mixture was boiled in an oil bath at 105-110 °C for two hours under refluxing. The mixture, which turned dark brown during boiling, was filtered while hot to remove the metallic selenium and the solvent was removed in a rotary evaporator. Water vapor distillation was applied to the residue to obtain the crude product. Quinoline-4-carboxaldehyde hydrate was crystallized from a mixture of ethanol/water (50:50) (Kaplan, 1941). Analysis data: Colorless needle crystals (%50), mp. 82-3 °C. IR (KBr): 3100-3000 (=C–H aromatic stretching), 2860 and 2760 (C–H aldehyde stretching), 1680 (C=O aldehyde stretching), 1580 and 1497 (C=N and C=C stretching), 1210, 1035, 845 and 750 (C–H bendings) cm^{-1}.

2.3.2. Synthesis of quinolin-8-carboxaldehyde

The mixture of 8-methylquinoline and selenium dioxide was moderately heated dry to 145-150 °C in a system equipped with an oxidizing tube. From this temperature, the reaction mixture was heated to 220 °C within 20 minutes and then raised to 250 °C within 2-3 minutes to remove unreacted 8-methylquinoline. The aldehyde was extracted from the cooled mixture with ether and crystallized from water (Seyhan and Fernelius, 1957). Analysis data: Light yellow needle crystals (%45), mp. 93-4 °C. IR (KBr): 3120–2980 (=C–H aromatic stretching), 2860 (C–H aldehyde stretching), 1670 (C=O aldehyde stretching), 1565 and 1500 (C=N and C=C stretching), 1240, 1165,1130, 860, 830 and 790 (C–H bendings) cm^{-1}.

2.3.3. Preparation of anhydrous ethanol

To 1 L of 95% ethanol in a 2 L round-bottomed flask, 250 g of calcium oxide was added which has been heated in an oven at high temperature for about six hours and cooled without contact with air. The mixture was boiled for six hours under a reflux condenser for 12 hours and then the alcohol was removed by distillation (Blatt, 1986).

2.3.4. Synthesis of pyrazolo[3,4-b]quinolinone compounds

To a solution of (1.0 mmol) heterylcarbaldehyde in anhydrous ethanol in a round bottom flask (1.0 mmol), a solution of the amine compound in anhydrous ethanol (1.0 mmol) and a solution of the dimedone compound in anhydrous ethanol (1.0 mmol) were added and brought to boiling over a water bath under a reflux condenser equipped with a $CaCl_2$ tube. The mixture was boiled for different time intervals for each compound under TLC control until the reaction was terminated. The crude product obtained from the cooled dark solution was filtered and purified by crystallization using appropriate solvents (Figure 1), (Gümüş 2009).

3. Results

Using each heterocyclic aldehyde, corresponding amines (3-methyl-5-aminopyrazole, 3-phenyl-5-aminopyrazole) and dimedone, six pyrazolo[3,4-*b*]quinolinone compounds (Compounds 1-6) containing the hetaryl group as a substituent were synthesized by one-pot multicomponent reaction (3-MCR) in anhydrous ethanol medium.

3.1. Spectroscopic Analysis Data of Compounds 1-6

3,7,7-Trimethyl-4-(pyridin-3-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one (Compound 1, Wagner et al. 2016, yield, 32%). FT-IR (KBr) cm^{-1}: 3223 (NH stretching), 3128-3026 (aromatic, =C-H stretching), 2964-2893 (alifatic, CH, CH_2 and CH_3, stretching), 1628-1474 (heteroaromatic ring, C=N and C=C stretching), 1380-1253 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 11.76 (s, 2-NH, 1H), 9.92 (s, 9-NH, 1H), 8.38 (m, 2'-CH, 1H), 8.23 (m, 6'-CH, 1H), 7.42 (m, 4'-CH, 1H), 7.18 (m, 5'-CH, 1H), 4.95 (s, 4-CH, 1H), 2.45 (d, 8-CH, J=16.9 Hz, 1H), 2.39 (d, 8-CH, J=16.9 Hz, 1H), 2.1 (d, 6-CH, J=16.1 Hz, 1H),

1.93 (d, 6-CH, J=16.1 Hz, 1H), 1.86 (s, 3-CH_3, 3H), 0.98 and 0.90 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 9.98 (3C-CH_3), 27.56 and 29.42 (7C-$(CH_3)_2$), 32.65 (4-CH), 33.56 (7-C), 41.64 (8-CH_2), 50.99 (6-CH_2), 103.69, 106.82, 123.92, 135.20, 135.83, 144.08, 146.89, 147.15, 149.29, 153.88 (carbons of aromatic and olefinic rings, 10C), 193.51 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 309 (10), 308 (90, M^+), 250 (100, -C_4H_{10}), 230 (60, -C_5H_4N), 78 (32, -$C_{13}H_{16}N_3O$). Elemental Analysis Results: $C_{18}H_{20}N_4O$, Found, %: C 70.03; H 6.48; N 18.21. Calculated, %: C 70.11; H 6.48; N 18.21.

3.2. *3,7,7-Trimethyl-4-(quinolin-4-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one* (Compound 2)

FT-IR (KBr) cm^{-1}: 3230-3195 (NH stretching), 3125-3040 (=C-H aromatic stretching), 2958-2893 (alifatic, CH, CH_2 and CH_3 stretching), 1618-1421 (aromatic and heteroaromatic ring, C=C and C=N stretching), 1382-1252 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 11.76 (br.s, 2-NH, 1H), 9.92 (s, 9-NH, 1H), 8.70-7.22 (m, aromatik, 6H), 5.72 (br.s, 4-CH, 1H), 2.51 (d, 8-CH, J=16.6 Hz, 1H), 2.44 (d, 8-CH, J=16.6 Hz, 1H), 2.08 (d, 6-CH, J=16.1 Hz, 1H), 1.86 (d, 6-CH, J=16.1 Hz, 1H), 1.61 (s, 3-CH_3, 3H), 0.99 and 0.90 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 10.33 (3C-CH_3), 27.59 and 29.47 (7C–$(CH_3)_2$), 32.57 (4-CH), 41.70 (8-CH_2), 50.96 (6-CH_2), 107.40, 121.81, 125.27, 126.37, 126.62, 129.39, 130.17, 136.16, 146.75, 150.73, 154.05 (carbons of aromatic and olefinic rings, 14C), 193.69 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 359 (10), 358 (60, M^+), 230 (100, -C_9H_6N), 129 (32, -$C_{13}H_{16}N_3O$). Elemental Analysis Results: $C_{22}H_{22}N_4O$, Found, %: C 73.80; H 6.13; N 15.54. Calculated, %: C 73.72; H 6.19; N 15.63.

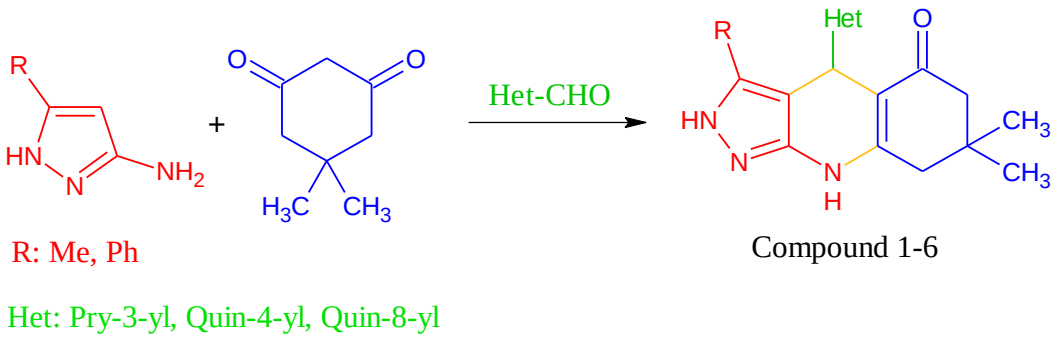


Figure 1. Synthesis of six novel hetaryl substituted pyrazolo[3,4-*b*]quinolinone compounds.

3.3. *3,7,7-Trimethyl-4-(quinolin-8-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one* (Compound 3)

FT-IR (KBr) cm^{-1}: 3220 (NH stretching, 3126-3046 (aromatic, =C-H stretching), 2971-2867 (alifatic, CH, CH_2 and CH_3 stretching), 1599-1431 (heteroaromatic ring, C=N and C=C stretching), 1382-1251 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 11.51 (br.s, 2-NH, 1H), 9.59 (s, 9-NH, 1H), 8.99-7.37 (m, aromatic, 6H), 6.46 (s, 4-CH, 1H), 2.52 (d, 8-CH, J=17.9 Hz, 1H), 2.48 (d, 8-CH, J=17.9 Hz, 1H), 2.09 (d, 6-CH, J=16.1 Hz, 1H), 1.88 (d, 6-CH, J=16.1 Hz, 1H), 1.66 (s, 3-CH_3, 3H), 1.02 and 1.01 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 10.48 (3C-CH_3), 27.81 and 29.62 (7C-$(CH_3)_2$), 28.85 (7-C), 32.66 (4-CH), 41.88 (8-CH_2), 51.32 (6-CH_2), 105.65, 108.65, 121.75, 125.99, 127.20, 128.14, 135.69, 136.76, 145.19, 147.05, 148.71, 149.83, 154.11 (carbons of aromatic and olefinic rings, 14C), 193.31 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 358 (100, M^+), 220 (66, -C_9H_6N), 130 (46, -$C_{13}H_{16}N_3O$). Elemental Analysis Results: $C_{22}H_{22}N_4O$, Found, %: C 73.65; H 6.24; N 15.71. Calculated, %: C 73.72; H 6.19; N 15.63.

3.4. *7,7-Dimethyl-3-phenyl-4-(pyridin-3-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one* (Compound 4)

FT-IR (KBr) cm^{-1}: 3299-3175 (NH stretching), 3125-3051 (=C-H aromatic stretching), 2950-2866 (alifatic, CH, CH_2 and CH_3 stretching), 1604-1425 (heteroaromatic ring, C=C and C=N stretching), 1373-1142 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 12.64 (s, 2-NH, 1H) 10.05 (s, 9-NH, 1H), 7.07-8.33 (m, aromatic, 6H), 5.36 (s, 4-CH, 1H), 2.48 (d, 8-CH, J=16.6 Hz, 1H), 2.38 (d, 8-CH, J=16.6 Hz, 1H), 2.14 (d, 6-CH, J=16.1 Hz, 1H), 1.94 (d, 6-CH, J=16.1 Hz, 1H), 0.99 and 0.82 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 27.22 and 29.52 (7C–$(CH_3)_2$), 32.66 (7-C), 33.88 (4-CH), 41.48 (8-CH_2), 50.95 (6-CH_2), 103.07, 107.41, 123.82, 126.67, 128.71, 129.47, 129.87, 135.39, 143.23, 147.26, 149.28, 153.26 (aromatic and olefinic ring carbons, 16C), 193.45 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 371 (21), 370 (100, M^+), 292 (55, -C_4H_5N), 78 (45, -$C_{18}H_{18}N_3O$). Elemental Analysis Results: $C_{23}H_{22}N_4O$, Found, %: C 74.65; H 5.89; N 15.19. Calculated, %: C 74.57; H 5.99; N 15.12.

3.5. *7,7-Dimethyl-3-phenyl-4-(quinolin-4-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one* (Compound 5)

FT-IR (KBr) cm^{-1}: 3300-3195 (NH stretching), 3125-3040 (aromatic, =C-H stretching), 2958-2893 (alifatic, CH_3, CH_2 and CH stretching), 1585-1421 (heteroaromatic ring, C=C and C=N stretching), 1382-1252 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 12.53 (br.s, 2-NH, 1H), 10.20 (s, 9-NH, 1H), 8.60-7.13 (m, aromatic, 11H), 6.06 (br.s, 4-CH, 1H), 2.55 (d, 8-CH, J=16.5 Hz, 1H), 2.42 (d, 8-CH, J=16.5 Hz, 1H), 2.11 (d, 6-CH, J=16.1 Hz, 1H), 1.85 (d, 6-CH, J=16.1

Hz, 1H), 0.99 and 0.79 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 27.14 and 29.61 (7C-$(CH_3)_2$), 32.52 (7-C), 40.82 (4-CH), 41.60 (8-CH_2), 50.96 (6-CH_2), 103.76, 107.96, 122.86, 125.90, 126.04, 127.39, 128.63, 128.99, 129.18, 129.57, 129.75, 139.05, 148.16, 148.50, 150.33, 153.40 (carbons of aromatic and olefinic rings, 20C), 193.71 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 421 (20, M+1), 420 (100, M^+), 296 (55, -C_9H_6N), 128 (50, -$C_{18}H_{18}N_3O$). Elemental Analysis Results: $C_{27}H_{24}N_4O$, Found, %: C 77.19; H 5.68; N 13.37. Calculated, %: C 77.12; H 5.75; N 13.32.

3.6. *7,7-Dimethyl-3-phenyl-4-(quinolin-8-yl)-2,4,6,7,8,9-hexahydro-5H-pyrazolo[3,4-b]quinolin-5-one* (Compound 6)

FT-IR (KBr) cm^{-1}: 3300-3195 (NH stretching), 3125-3040 (aromatic, =C-H stretching), 2958-2893 (alifatic, CH_3, CH_2 and CH stretching), 1585-1421 (heteroaromatic ring, C=C and C=N stretching), 1382-1252 (C-H bendings). ^{1}H-NMR (DMSO-d_6) δ ppm: 12.53 (br.s, 2-NH, 1H) 10.20 (s, 9-NH, 1H), 8.60-7.13 (m, aromatik, 11H), 6.06 (br.s, 4-CH, 1H), 2.55 (d, 8-CH, J=16.5 Hz, 1H), 2.42 (d, 8-CH, J=16.5 Hz, 1H), 2.11 (d, 6-CH, J=16.1 Hz, 1H), 1.85 (d, 6-CH, J=16.1 Hz, 1H), 0.99 and 0.79 (2s, 7-$(CH_3)_2$, 6H). ^{13}C-NMR (DMSO-d_6) δ ppm: 27.14 and 29.61 (7C-$(CH_3)_2$), 32.52 (7-C), 40.82 (4-CH), 41.60 (8-CH_2), 50.96 (6-CH_2), 103.76, 107.96, 122.86, 125.90, 126.04, 127.39, 128.63, 128.99, 129.18, 129.57, 129.75, 139.05, 148.16, 148.50, 150.33, 153.40 (carbons of aromatic and olefinic rings, 20C), 193.71 (5-C carbonyl carbon). GC-MS (MeOH) m/z (%): 421 (20, M+1), 420 (100, M^+), 296 (55, -C_9H_6N), 128 (50, -$C_{18}H_{18}N_3O$). Elemental Analysis Results: $C_{27}H_{24}N_4O$, Found, %: C 77.19; H 5.68; N 13.37. Calculated, %: C 77.12; H 5.75; N 13.32.

4. Discussion

Cyclocondensation can theoretically occur via two pathways. However, in the studies performed so far, it has been reported that pathway B is not followed during the reaction and only products via pathway A are formed (Quiroga et al., 1998a; Quiroga et al., 1998b; Quiroga et al., 2001; Lipson et al., 2003b).

Since there will be no interaction between 4-H and 9-NH in the NMR data of the linear products formed by pathway A, they will give singlet peaks when they resonate (Gümüş 2009). In fact, in the ^{1}H NMR spectra of compounds 1, 2, 3, 4, 5, and 6, 4-H and 9-NH gave singlet peaks with integration ratios of 1:1. This situation is inconsistent with the product being formed in the angular structure via pathway B, since H and NH are adjacent in the angular structure and spin-spin interactions would be expected between them. Since no such interaction was observed, the product formed is the linear product (Figure 2).

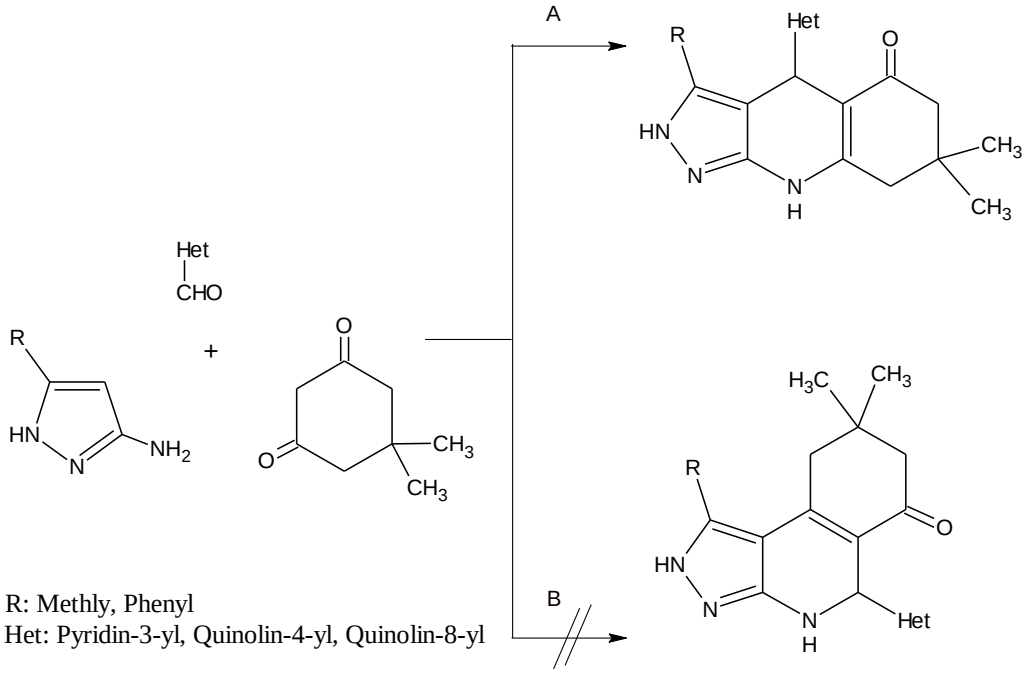


Figure 2. Theoretical possibilities of the cyclocondenzation reaction.

When the resonance structures of 3(5)-Amino-5(3)-methylpyrazole are examined, it is seen that the electron density on the fourth carbon is quite high as indicated in the resonance structures, so it has the ability to attack as a nucleophile (Figure 3). In addition, the electron density on the fourth carbon increases again because the amino group substituted on the pyrazole activates the ring by giving electrons to the ring (Figure 4).

Based on this information, we can propose the following mechanisms (Figure 5) for the formation of compound 1.

In pathway A, a Knoevenagel intermediate is formed between the aldehyde and the dimedone, and then another intermediate is formed by Michael addition to this α,β-unsaturated intermediate by the attack of

electrons at the fourth carbon of the pyrazole. Due to resonance, this intermediate is formed to a higher degree in pathway B, which we will discuss later, and therefore the reaction only follows pathway A. In the next step of the reaction, an intramolecular ring condensation takes place between the substituted amino group of the pyrazole and the keto-group of the dimedone to form the main product. We can propose the following mechanism for path B.

As a result of Michael's addition to the α, β-unsaturated Knoevenagel intermediate, an intermediate is formed by attacking the lone pair in the amino group as a substituent in the pyrazole ring. When this intermediate is studied, it is believed that the nitrogen atom is positively charged, and since nitrogen is an electronegative atom, it will avoid this road. Therefore, the reaction will not follow pathway B (Figure 6) and will proceed via pathway A. Indeed, the NMR data of the products formed as a result of the reaction support these views (Table 1 and Table 2).

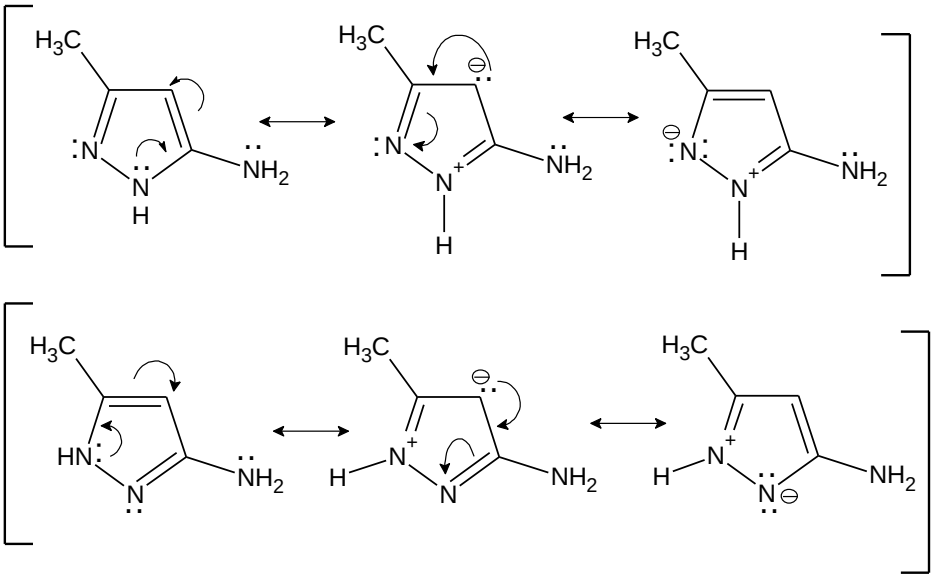


Figure 3. Resonance structures of 3(5)-Amino-5(3)-methylpyrazole.

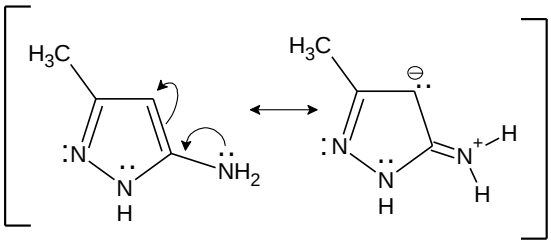


Figure 4. The amino group substituted on the pyrazole activates the ring by giving electrons.

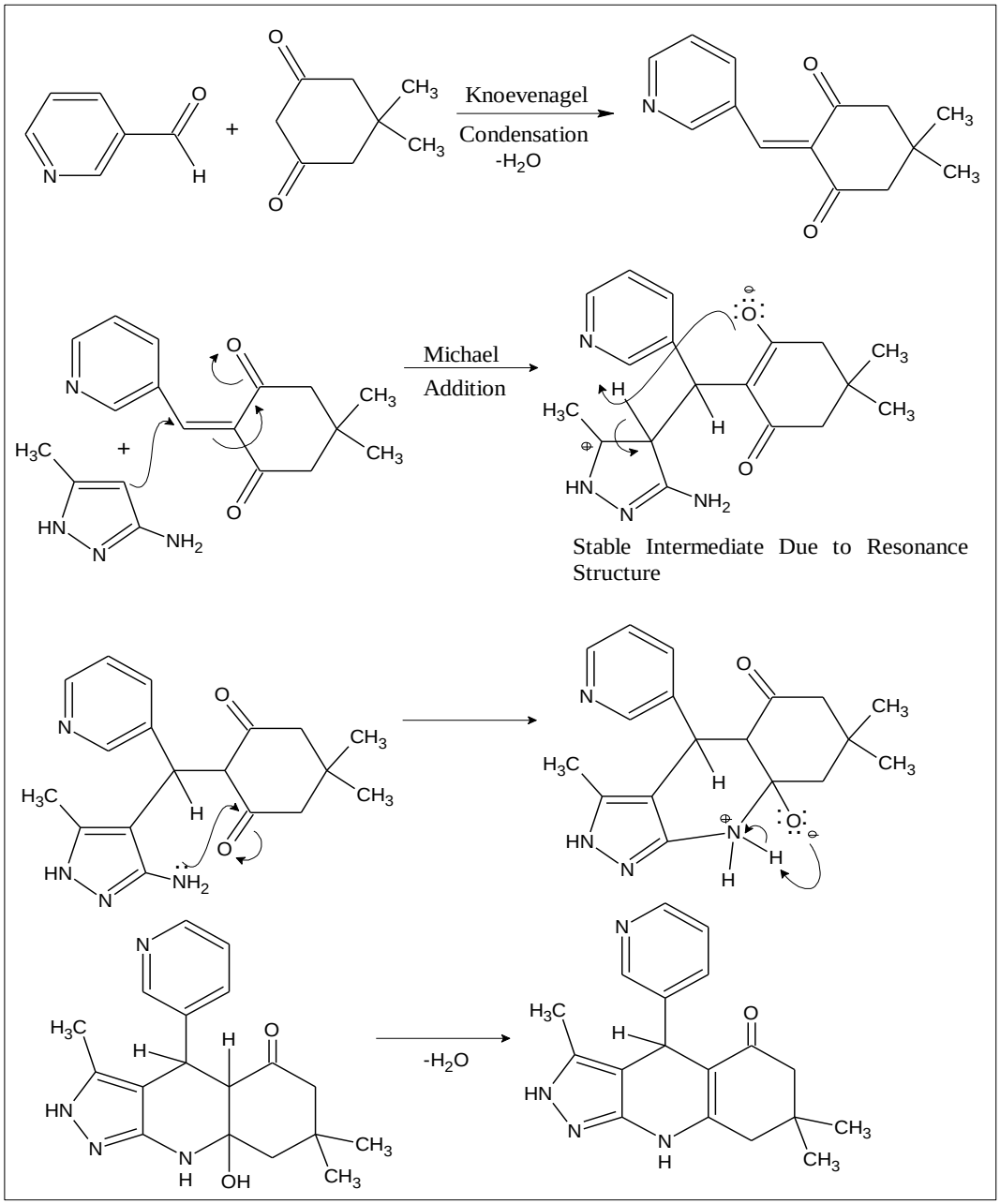


Figure 5. Mechanism of the product formed via pathway A.

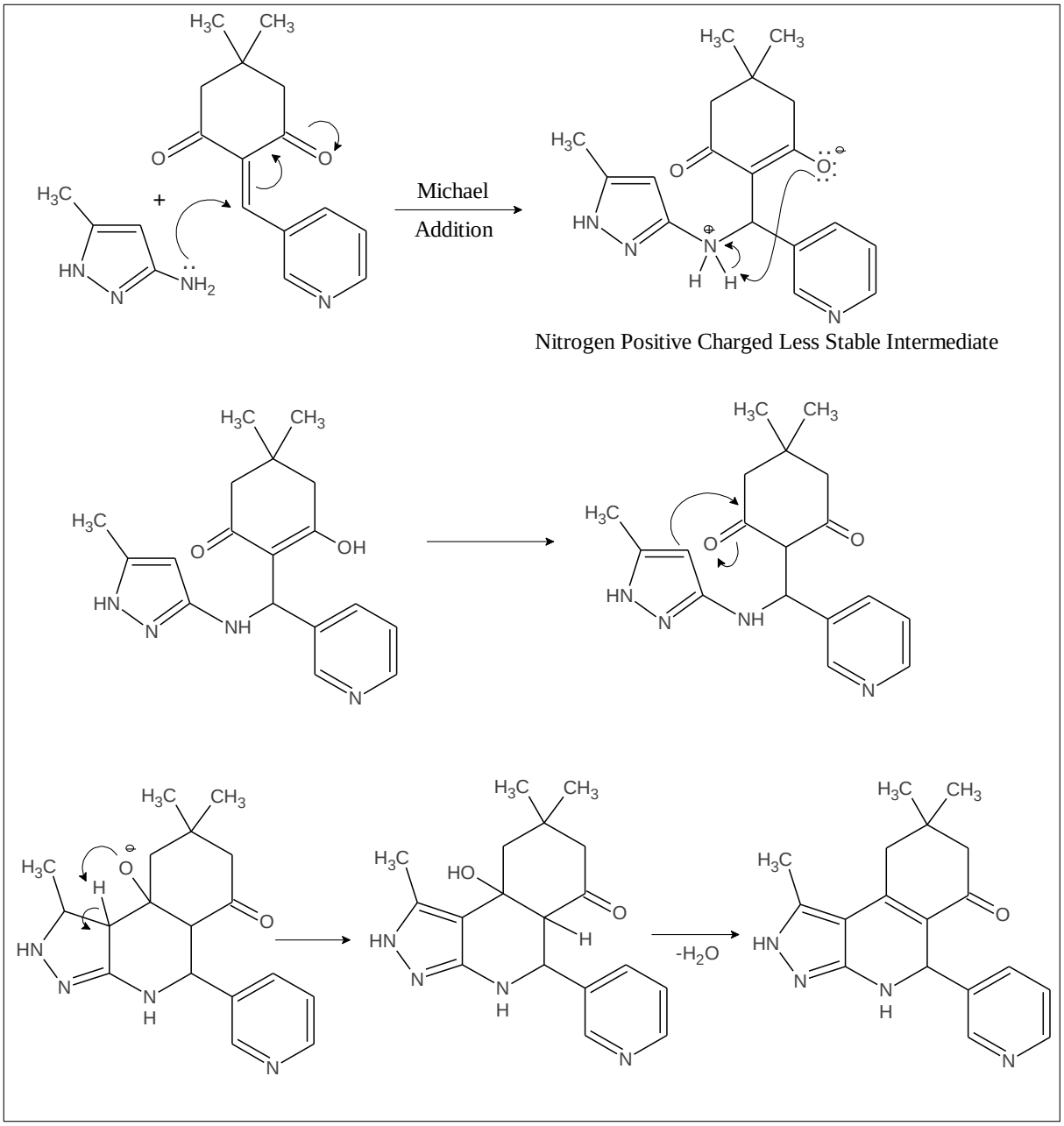
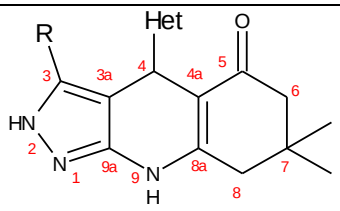


Figure 6. Mechanism of the product formed via pathway B.

Table 1. ^{1}H-NMR values of compounds 1-6 δ (ppm)



R: Methyl, Phenyl

Het: Pyr-3-yl, Quin-4-yl, Quin-8-yl

Compound	2-H br.s, 1H	3-CH_3 s, 3H	4-Het. m	4-H s, 1H	6-H 2d, 2H	7-C(Me)$_2$ 2s, 6H	8-H 2d, 2H	9-H br.s, 1H
1	11.76	1.86	7.18-8.38	4.95	1.93 2.10	0.90 0.98	2.39 2.45	9.92
2	11.76	1.61	7.22-8.70	5.72	1.86 2.08	0.90 0.99	2.44 2.51	9.92
3	11.51	1.66	7.37-8.99	6.46	1.88 2.09	1.01 1.02	2.48 2.52	9.59
	2-H br.s, 1H	3-Ph m, 5H	4-Het. m	4-H s, 1H	6-H 2d, 2H	7-C(Me)$_2$ s, 6H	8-H 2d, 2H	9-H br.s, 1H
4	12.64	7.38-7.48	7.07-8.33	5.36	1.94 2.14	0.82 0.99	2.38 2.48	10.05
5	12.53	7.30-7.43	7.13-8.60	6.06	1.85 2.11	0.79 0.99	2.42 2.55	10.20
6	12.35	7.33-7.38	7.10-8.88	6.75	1.80 2.10	0.85 1.00	2.42 2.54	9.91

Table 2. ^{13}C-NMR values of compounds 1-6 δ (ppm)

Compound	1	2	3	4	5	6
7-C(Me)$_2$	27.56 29.42	27.59 29.47	27.81 29.62	27.22 29.52	27.14 29.61	27.19 29.80
3-Me	9.98	10.33	10.48	-	-	-
C-8	41.64	41.70	41.88	41.48	41.60	41.71
C-7	33.56	32.57	28.85	32.66	32.52	32.60
C-6	50.99	50.96	51.32	50.95	50.96	51.31
C-5	193.51	193.69	193.31	193.45	193.71	193.69
C-4	32.65	32.57	32.66	33.88	32.70	32.60

Mass spectral analyses of these synthesized compounds were performed to confirm their structures. The MS spectra of compounds 1, 2, 3, 4, 5 and 6 revealed that, the m/z ratios obtained from the observed molecular ion peaks are 385, 358, 358, 370, 420 and 420, respectively. These values determine the molecular weights of the synthesized products. Both these molecular peaks and their subsequent general (a-a') fragmentation prove the proposed structures of the compounds (Figure 7 and Figure 8).

When the FT-IR spectra of the obtained compounds are examined, aromatic =C-H stretching, aliphatic C-H stretching, C=O stretching, C=N and C-N stretching vibrations characteristic for nitrogen-containing heterocyclic compounds are observed in the region characteristic for them. The strong primary amine absorption bands of the heteroaromatic amines used as starting materials in the reactions were not observed in the spectra of the products (Figure 9). Physical properties, yields and elemental analysis values of all synthesized compounds are given in Table 3.

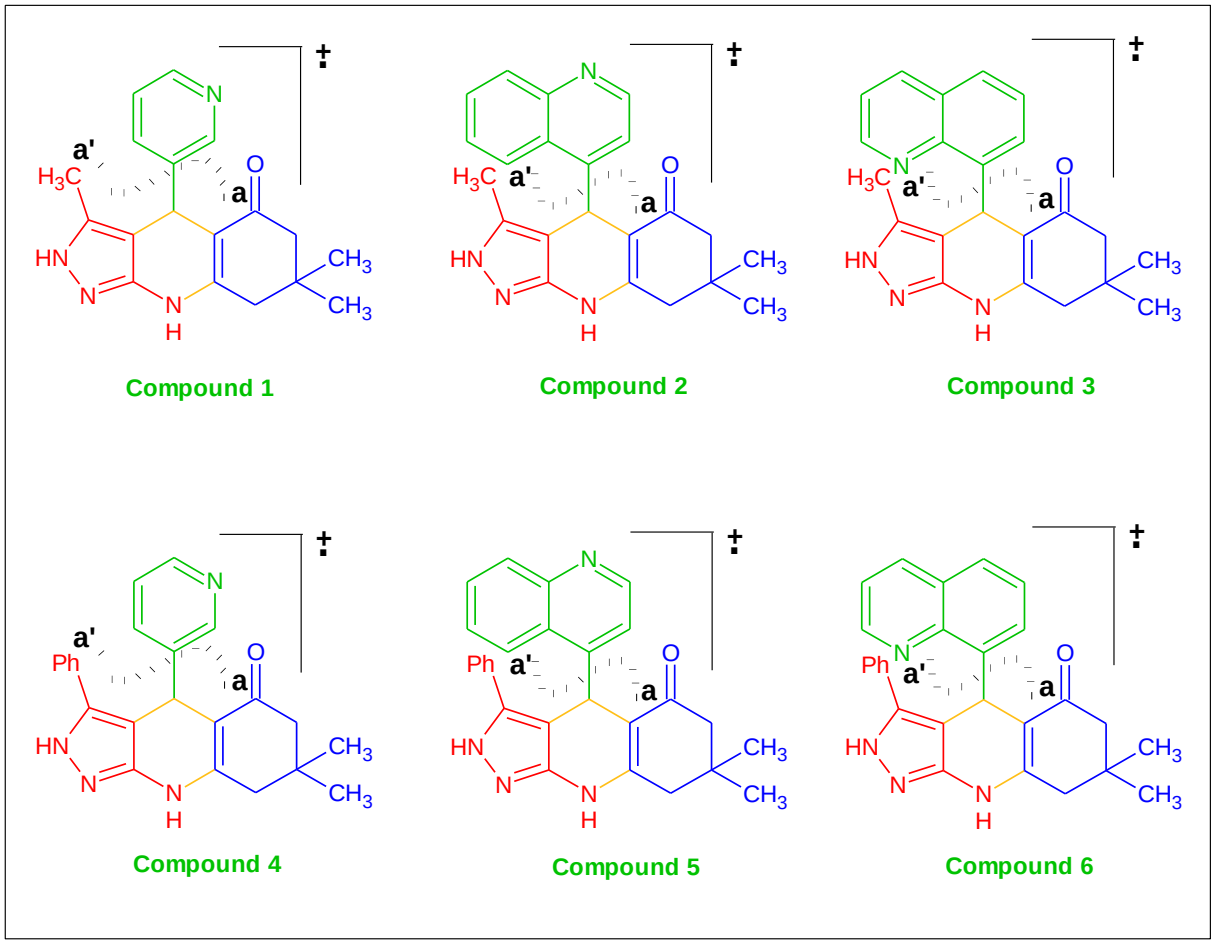


Figure 7. General fragmentations of compounds 1-6.

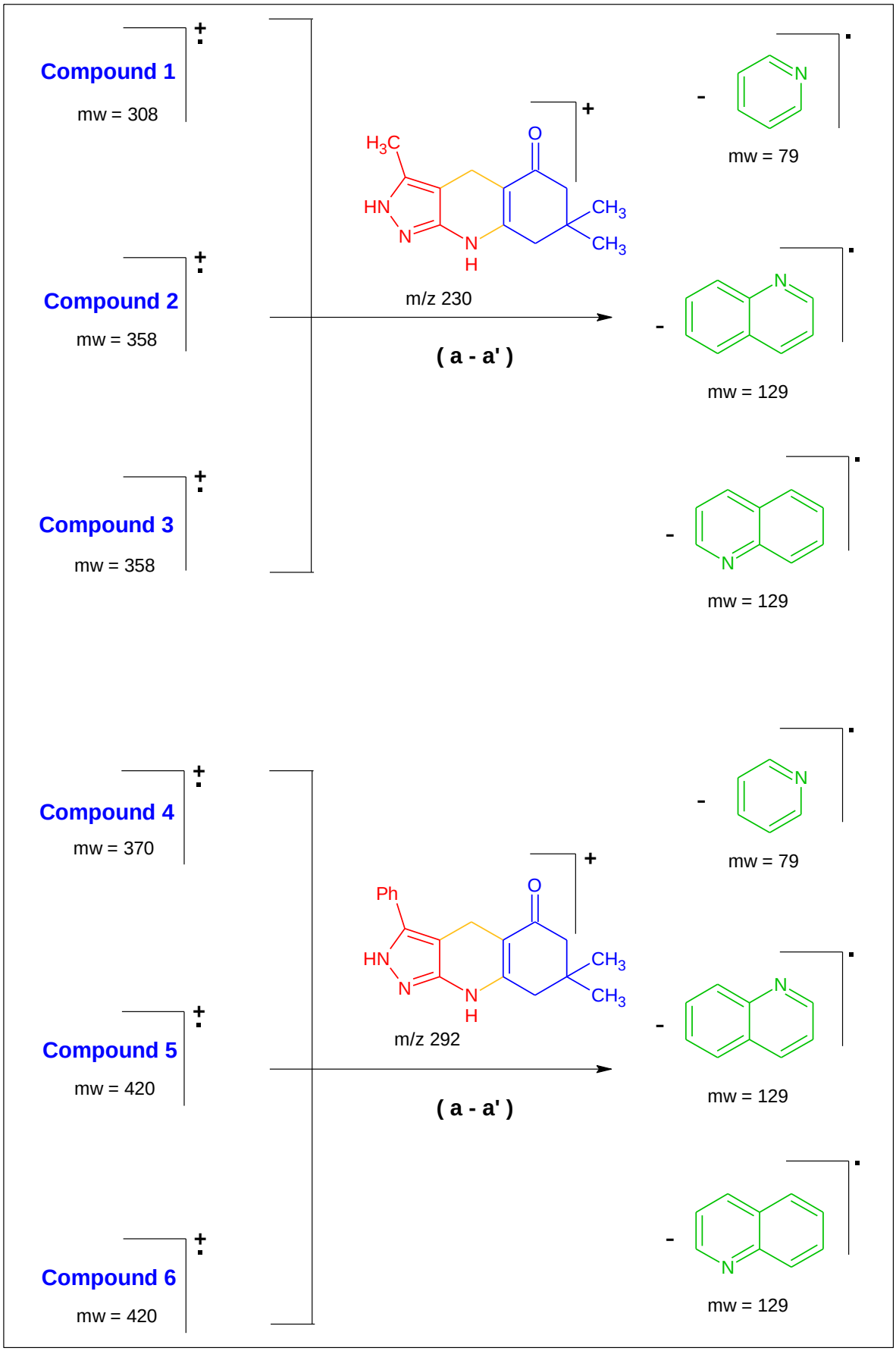


Figure 8. Comparison of fragmentation values of compounds 1-6.

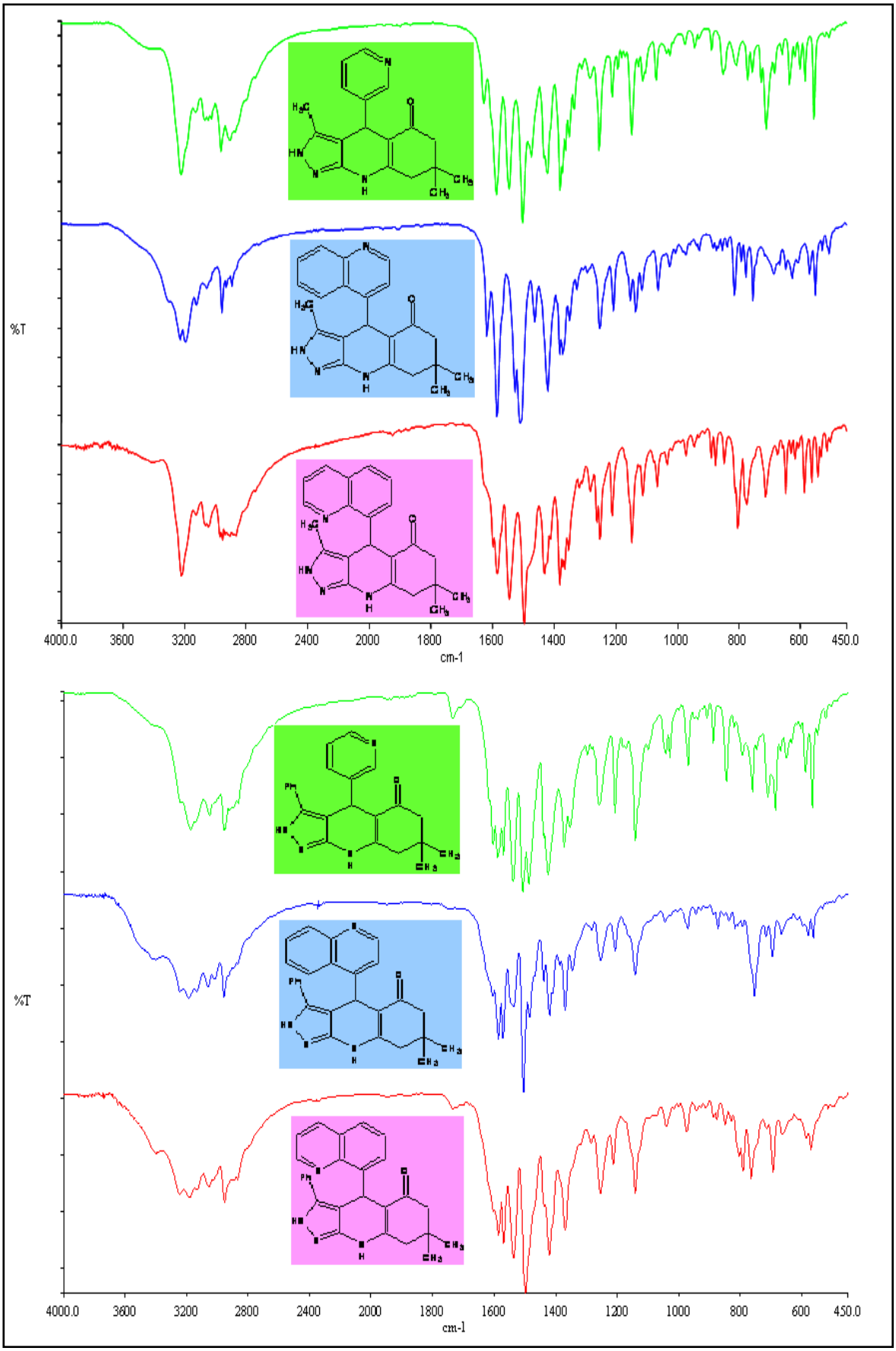


Figure 9. Comparison of FT-IR spectra of compounds 1-6.

Table 3. Physical properties, yields and elemental analysis values of compounds 1-6

Compound	Molecular formula	mw (g/mol)	Melting point (°C)	Yield (%)	Crystal shape	Crystal color	Elemental Analysis Calculated/Found		
							C	H	N
1	$C_{18}H_{20}N_4O$	308	307-8	83	powdered	light yellow	70.11 70.03	6.54 6.48	18.17 18.21
2	$C_{22}H_{22}N_4O$	358	304-5	72	powdered	light yellow	73.72 73.80	6.19 6.13	15.63 15.54
3	$C_{22}H_{22}N_4O$	358	301-2	78	powdered	light yellow	73.72 73.65	6.19 6.24	15.63 15.71
4	$C_{23}H_{22}N_4O$	370	298-9	70	powdered	light yellow	74.57 74.65	5.99 5.89	15.12 15.19
5	$C_{27}H_{24}N_4O$	420	225-6	63	powdered	light yellow	77.12 77.19	5.75 5.68	13.32 13.37
6	$C_{27}H_{24}N_4O$	420	270-1	68	powdered	light yellow	77.12 77.05	5.75 5.81	13.32 13.40

4. Conclusion

In conclusion, the synthesis of six compounds by one-pot multicomponent cycloaddition reaction technique was successfully carried out in this study. The crude products were obtained in very good yields and purified by crystallization. The structures of the compounds, which were found to be completely pure as a result of chromatographic studies, were elucidated by spectroscopic methods and elemental analysis.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	M.K.G.	S.K.
C	80	20
D	80	20
S	10	90
DCP	90	10
DAI	80	20
L	90	10
W	80	20
CR	80	20
SR	80	20
PM	20	80
FA	20	80

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study since there was no study on animals or humans.

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This study is based on Mustafa Kemal Gümüş's doctorate thesis, conducted under the supervision of Şeniz Kaban.

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Bellevalia Pseudolongipes PLANT: COMPREHENSIVE ANALYSIS OF THE ELEMENTAL COMPOSITION AND TOTAL PHENOLIC AND FLAVONOID CONTENTS

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Abstract: *Bellevalia pseudolongipes* is a recently described plant species, whose mineral and biochemical composition have not yet been reported. Thus, this study examined the mineral composition and total phenolic and flavonoid contents of the *B. pseudolongipes* plant. Elemental analysis revealed that the plant contained high levels of calcium (22379.556 ± 025 ppm) and potassium (19721.157 ± 005 ppm). Phenolic compound analysis demonstrated a high total phenolic content (0.24 ± 0.004 mg gallic acid equivalent/g sample), thus highlighting the antioxidant capacity of the plant. Additionally, the assessment of flavonoid content (0.043 ± 0.001 mg catechin equivalent/100 g sample) indicated the potential use of the *B. pseudolongipes* plant as a source of antioxidants. These findings underscore the value of *B. pseudolongipes* as a natural resource that is rich in antioxidant, mineral, and phenolic content, while also providing a crucial foundation for researchers interested in exploring its pharmacological, medical, and industrial potential. The results of this study contribute to our understanding of the biological and health values of plants, thereby providing a useful tool for the development of products that are derived from natural sources and innovative solutions that contribute to human health.

Keywords: *Bellevalia pseudolongipes*, Elemental content, Total phenolics, Total flavonoids

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1. Introduction

Plants play a crucial role in ecosystems and contribute to their overall biodiversity. They also provide medical, economic, and environmental benefits. Trace elements are minerals found in small quantities in living tissues, and their excess or absence can result in a range of health issues (Akınoğlu and Erdal, 2024; Yolbaş, 2024a).

Plant secondary metabolites can be classified into terpenes, phenolics, and nitrogenous compounds (Tekin, 2022). Among the bioactive compounds that are present in plants, phenolic compounds have attracted considerable attention owing to their antioxidant, antimicrobial, and anti-inflammatory properties. These compounds are essential metabolites in almost all plant parts and protect plants against biotic and abiotic stresses (Borowska and Szajdek, 2003; Dietrich, 2004; Yolbaş, 2024c). Consequently, determining the biochemical composition and mineral content of plants is of great significance (Kandemir et al., 2022; Jegadeeshwari et al., 2023).

Flavonoids are a class of low-molecular-weight phenolic compounds that are commonly found in the leaves, flowers, and fruits of plants (Okar et al., 1997; Sghaier et al., 2011). They can trap free radicals (Miller and Ruiz-Larrea, 2002) and exhibit diverse biological effects, such as anti-inflammatory, anti-allergic, and antiviral properties (Shi et al., 2001; Yolbaş, 2024b; Saraçoğlu, 2024b). Although the human body cannot produce flavonoids, they can be obtained from fruits and vegetables (Kılıç, 2020); the beneficial effects of plant-derived flavonoids have been reported previously (Panche et al., 2016).

With the advancement of instrumental analytical techniques, numerous elements can be determined more accurately in a short period. Trace elemental analysis, which is the most important research technique in analytical chemistry, has attracted attention owing to its ability to provide insights into the functions of trace elements in various fields, such as high-purity materials, geochemistry, environmental pollution, pharmaceuticals, and their effects on the human body and metabolism (Saraçoğlu, 2024a).

Bellevalia is a genus of plants in the Asparagaceae family that comprises 74 species (Johnson, 2003). *Bellevalia pseudolongipes* has recently been described and illustrated as a new species from the Siirt province in southeastern Anatolia, Türkiye. It is morphologically similar to *B. longipes*, but differs in morphological features and chromosome number (Karabacak et al., 2014). Several studies have been conducted on the biochemical contents of the *Bellevalia* species and their

therapeutic properties (Yildirim et al., 2013; Savio et al., 2019; Ouelbani et al., 2020), and researchers have even investigated the biochemical properties of *B. pseudolongipes* (Balos, 2021). However, no studies have evaluated its mineral content; therefore, determining the mineral composition of this new species, *B. pseudolongipes*, provides insights into the biodiversity of the genus *Bellevalia*.

For the first time, this research aims to analyze the elemental composition of the *B. pseudolongipes* plant and measure its total phenolic and flavonoid contents using methanol extraction. This study will help us understand its potential health benefits and industrial applications by providing missing information regarding its biochemical profile. The results presented in this study will form the basis for understanding the biological activities of the plant and identifying potential areas of use.

2. Materials and Methods

2.1. Sample Collection

Fifty *B. pseudolongipes* plants that grew in their natural habitat were collected from the Pervari district of Siirt province in early May 2023. The collected plant samples, including their bulbs, roots, stems, flowers, and leaves, were dried whole in a dark room at 24 °C for one month. The dried *B. pseudolongipes* samples were then ground into a powder under the same conditions and stored in a closed container in a dark room until the analysis (Yolbaş, 2023).

Figure 1. The *B. pseudolongipes* plant.

2.2. Extract Preparation

A powdered plant sample (0.2 g) was mixed with 5 mL of 75% methanol (Merck, Darmstadt, Germany) containing 0.1% phosphoric acid (Merck, Darmstadt, Germany). The mixture was then homogenized for 30 s at 600 rpm using an Ultra-Turrax homogenizer (MS3-MaxiHomo35, Osaka, Japan). Subsequently, the sample was centrifuged at 2500 rpm (Archer LC-05 A, Istanbul, Türkiye) for 10 min at 24 °C. The resulting supernatant was incubated in an ultrasonic water bath at 25 °C for 15 min. The extraction procedure was conducted twice, and the obtained extracts were combined. The final extract volume was standardized to 10 mL using methanol, and the resulting extract was placed in 100 µL tubes and stored in the refrigerator (5 °C).

2.3. Total Phenolic Content

For the determination of the total phenolic substances, the method developed by Çapanoğlu et al. (2013) was employed, with slight modifications. The *B. pseudolongipes* extract (100 µL) was mixed with ultrapure water (900 µL, 18.2 MΩ, Arium Pro Ultraclean Water System, Sartorius, Göttingen, Germany) and Folin–Ciocalteu reagent (5 mL, 0.2 M). The blend was vigorously shaken and left undisturbed for 8 min. Subsequently, a sodium carbonate solution (5 mL, 7.5%) was introduced, and the mixture was vortexed for 20 s and stored in the dark at 22–24 °C for 2 h. The absorbance was recorded at 765 nm using a Biochrome Libra S70 double-beam spectrophotometer (Cambridge, UK). Quantification was conducted using the gallic acid standard to establish the calibration curve, and analyses were performed in triplicate.

2.4. Total Flavonoid Content

For the determination of the total flavonoid substances, the method developed by Zhishen et al. (1999) was employed, with slight modifications. The *B. pseudolongipes* extract (0.4 mL) was transferred to a 10 mL volumetric flask, and 4 mL of distilled water was added. Next, a $NaNO_2$ solution (0.3 mL, 5%) was added, and the mixture was allowed to rest for 5 min. Subsequently, an $AlCl_3$ solution (0.3 mL, 10%) was introduced, and the mixture rested for 6 min. Finally, a NaOH solution (2 mL, 1 M) and 3 mL of distilled water were added, and the mixture was shaken. The absorbance was measured at 510 nm using a Biochrome Libra S70 double-beam spectrophotometer (Cambridge, UK), with pure water used for the blank reading. Calculations were conducted using the catechin standard to establish the calibration curve. All analyses were performed in triplicate.

2.5. Elemental Analysis

2.5.1. Sample preparation

For the analysis using inductively coupled plasma mass spectrometry (ICP–MS), powdered *B. pseudolongipes* samples (1 g each) were placed in individual microwave digestion Teflon vessels (CEM brand MARS 6 One Touch microwave oven, Matthews, NC, USA). A concentrated nitric acid solution (65%, 10 mL, Merck, Darmstadt, Germany) was added to each sample, and a blank sample containing only nitric acid (65%, 10 mL) was prepared. The vessels were then sealed, placed in the microwave oven, and digested. The temperature was increased from room temperature (22–24 °C) to 210 °C within 25 min and was maintained at 210 °C for 15 min. The samples were cooled to 22–24 °C and transferred to volumetric flasks (50 mL). Ultrapure water was added to attain the final volume.

2.5.2. ICP–MS analysis

The ICP–MS calibration solutions (Table 1) were obtained by diluting commercially available multi-element standards with Suprapur nitric acid (1%, Millipore Sigma, Burlington, MA, USA) and ultrapure water. Appropriate sample dilutions were performed, and the solutions were analyzed using a NexION 2000 B ICP mass spectrometer (PerkinElmer, Waltham, MA, USA) equipped with a quartz fogger, cyclonic fog chamber, and an integrated automatic sampling device under the operating conditions summarized in Table 2. Yttrium (^{89}Y) was used as the internal standard. A wash solution containing Suprapur nitric acid (1%) and ultrapure water at the concentrations specified in Table 1 was prepared for clean-up. The samples were injected into a cyclonic fog chamber using Ar gas via a peristaltic pump. A large quantity of helium gas was also used to prevent interference. The Syngistix software for ICP–MS version 2.2 (PerkinElmer, Waltham, MA, USA) was used for the device settings, data collection, and analysis. Analyses were conducted in triplicate.

Table 1. Calibration curve standard solutions

Analytes	Std1 (ppm)	Std2 (ppm)	Std3 (ppm)	Std4 (ppm)	Std5 (ppm)	Std6 (ppm)	Internal standard
Li, B, Al, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Nb, Mo, Ru, Pd, Ag, Cd, Sn, Ba, Hf, Ta, W, Au, Pb, U	0.5	1	5	25	50	00	^{89}Y
Na, Mg, K, Ca, Fe	25	50	2.50	1250	2500	5000	

Table 2. ICP–MS operating conditions

Parameter	Description/Value
Nebulizer	MEINHARD plus Classic Type C
Spray chamber	Glass cyclonic (baffled), 4 °C
Torch	One piece w/ 2.5 mm Quartz Injector
Injector	2.0 mm i.d.
Nebulizer flow	Optimized for < 2% oxides
RF (Radio frequency) power	1600 W
Cones	Ni
Replicates	3
Dwell time	50 ms
Aerosol dilution	Set to 2.5×
Sample delivery rate	350 µL/min
Rinse time	45 s
Nebulizer gas flow rate	0.93 L/min
Deflector voltage	Approximately 12 V
Analog stage voltage	Approximately 1750 V
Pulse stage voltage	1100 V
Discriminator threshold	26
Sample tubing (orange-yellow)	Flared PVC pump tubes 0.51 mm/0.89 mm
Internal standard tubing (orange-red)	Flared PVC pump tubes 0.19 mm/0.91 mm
Peristaltic pump speed	35 rpm
Alternating current (AC) rod offset	Approximately 4

3. Results and Discussion

3.1. Elemental Analysis Results

Elemental analysis of the *B. pseudolongipes* plant was conducted using the ICP–MS method with microwave-assisted dissolution. According to the results, the concentrations of 34 different elements (Al, As, Au, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Ga, Hf, K, Li, Mg, Mn, Mo, Na, Nb, Ni, Pb, Pd, Rb, Ru, Se, Sn, Sr, Ta, Ti, U, V, W, and Zn) were determined (Table 3). Within the detection limits, the element with the highest concentration was Ca (22379.556 ± 0.025 ppm), whereas the element with the lowest concentration was Ru (0.524 ± 0.004 ppm). The concentrations of B, Na, and Mg were 137.436 ± 0.016, 5670.721 ± 0.000, and 4246.435 ± 0.003 ppm, respectively.

Organisms require not only protein, carbohydrates, and vitamins but also micronutrients for their normal growth and biological functioning (Onat et al., 2021). These micronutrients play crucial roles in various enzymatic reactions in metabolism and are vital for living organisms (Şap, 2012). In particular, copper plays a critical role in bodily functions and is one of the fundamental building blocks of hair, skin, internal organs, and bones (Kahvecioğlu et al., 2003). Zinc is required by various enzymes and hormones, thereby influencing their functions, and is involved in the renewal of cells and tissues (Özkaya et al., 1991). Iron is a functional component of hemoglobin found in red blood cells that is crucial for oxygen transportation (Yolbaş, 2023). Magnesium is essential for several metabolic processes, particularly in ensuring the proper spread of sodium, potassium, and calcium in cell membranes via cellular pumps (Wilkie and Cordess, 1994). These findings demonstrate the critical role of micronutrients in the healthy functioning of living organisms.

Various plant species have been subjected to numerous

elemental analyses using different methods. However, this is the first study on the *B. pseudolongipes* plant regarding elemental analysis, and significant findings have been obtained when compared to studies on elemental determination in other plants. The presence of metals in plants is dependent on environmental factors, such as the physical and chemical structure of the soil and the potential of plants to absorb metals from the soil (Zurera-Cosano et al., 1989; Erdoğrul et al., 2005). Therefore, when comparing the element analysis results of *B. pseudolongipes* with those of other plants, similarities and differences were apparent.

The presence of K and Ca in high concentrations in the digest indicated that this plant might contribute to regulating cellular functions, maintaining water balance, promoting bone health, and participating in other vital functions (Kuyumcu, 2009; Tosun, 2009). Owing to the significant amounts of zinc and selenium, this plant could protect the body against free radicals and increase resistance to various diseases (Atlihan et al., 1990). Heavy metals, such as Pb, Cu, and Cd, were detected at concentrations of 20.106 ± 001, 13.628 ± 005, and 1.172 ± 013 ppm, respectively (Karaaslan, 2009). These values were higher than expected because the area where the plant samples were collected is close to the highway and human settlement. Investigating plant elemental distribution is essential because it helps determine their mineral and nutritional contents.

This study was subject to limitations, including the inability to comprehensively evaluate the pollution effects on the sampled area and the restriction of samples collected from a limited region. In future studies, it is essential to collect samples from diverse geographical regions and conduct a more extensive investigation into the effects of pollution. This preliminary study represents a pioneering effort in this field and offers crucial findings that will serve as a reference for future research.

Table 3. ICP–MS elemental analysis results

Li 7 Helium KED High (ppm)	B 11 Helium KED High (ppm)	Na 23 Helium KED High (ppm)	Mg 24 Helium KED High (ppm)	Al 27 Helium KED High (ppm)
8.954±030	137.436±016	5670.721±000	4246.435±003	3309.567±004
Cr 52 Helium KED High (ppm)	Mn 55 Helium KED High (ppm)	Fe 57 Helium KED High (ppm)	Co 59 Helium KED High (ppm)	Ni 60 Helium KED High (ppm)
11.688±001	60.959±004	2427.598±001	2.167±003	26.334±002
Se 82 Helium KED High (ppm)	Rb 85 Helium KED High (ppm)	Sr 88 Helium KED High (ppm)	Nb 93 Helium KED High (ppm)	Mo 98 Helium KED High (ppm)
18.237±052	4.929±002	453.384±014	1.138±001	1.609±007
Sn 118 Helium KED High (ppm)	Ba 138 Helium KED High (ppm)	Hf 180 Helium KED High (ppm)	Ta 181 Helium KED High (ppm)	W 184 Helium KED High (ppm)
1.710±011	44.328±011	1.120±021	1.690±002	1.936±001
K 39 Helium KED High (ppm)	Ca 43 Helium KED High (ppm)	Ti 48 Helium KED High (ppm)	V 51 Helium KED High (ppm)	Au 197 Helium KED High (ppm)
19721.157±005	22379.556±025	50.890±006	7.410±001	2.127±002
Cu 63 Helium KED High (ppm)	Zn 66 Helium KED High (ppm)	Ga 69 Helium KED High (ppm)	As 75 Helium KED High (ppm)	Pb 208 Helium KED High (ppm)
13.628±005	445.185±001	9.479±002	1.563±024	20.106±001
Ru 102 Helium KED High (ppm)	Pd 106 Helium KED High (ppm)	Ag 107 Helium KED High (ppm)	Cd 111 Helium KED High (ppm)	U 238 Helium KED High (ppm)
0.524±004	1.309±002	1.479±011	1.172±013	5.361±000

3.2. Total Phenolic Content

Oxidative damage contributes to various diseases, including cancer, hypertension, atherosclerosis, bronchitis, asthma, diabetes, Parkinson's disease, liver diseases, Down syndrome, aging, and rheumatism, by affecting cellular components and altering nucleic acid bases in DNA (Matés and Sánchez-Jiménez, 2000). Phenolic compounds are significant phytochemicals that confer antioxidant activity to plant materials (Pizzale et al., 2002; Fattahi et al., 2012). Epidemiological studies have demonstrated the protective effects of plant sources against reactive oxygen species. This protection is attributed to compounds such as vitamin C, vitamin E, carotenoids, glutathione, flavonoids, and phenolic acids

present in fruits and vegetables (Halvorsen et al., 2002). In this study, the total phenolic content of *B. pseudolongipes* was 0.24 ± 0.004 mg gallic acid/g sample. Phenolic compounds occur naturally in plants and possess antioxidant properties. For example, *Bellevalia saviczii* is a plant with anti-rheumatic and anti-inflammatory properties located in Iraq. The anti-inflammatory effects of a certain compound, dracol, which inhibits intracellular Ca^{2+} release and suppresses cytokine secretion, have been observed in this plant (Savio et al., 2019). Additionally, *Bellevalia gracilis* exhibits a high antioxidant activity (Yildirim et al., 2013). Therefore, the phenolic content observed in *B. pseudolongipes* underscores its ability to mitigate oxidative stress at the cellular level by increasing the antioxidant capacities of cells.

Balos (2021) have previously reported variations in the phenolic content between the bulb, leaf, and flower components of *B. pseudolongipes*, where the highest phenolic content was observed in the maceration extraction method (ethanol extract) of the flower. Tekin (2022) investigated the phenolic content in different parts of the *B. sasonii* plant. Their results revealed that the highest phenolic amount was determined in the onion extract of the plant, whereas the lowest was observed in the stem extract. Different extraction methods and the selection of solvents employed significantly impact the bioactive compounds obtained. Therefore, selecting the appropriate extraction method and solvent is of great importance.

3.3. Total Flavonoid Content

Flavonoids are known for their antioxidant properties, which may help prevent several diseases by reducing oxidative stress at the cellular level. They are also known for their anti-inflammatory properties. The total flavonoid content of *B. pseudolongipes* was 0.043 ± 0.001 mg catechin/100 g sample, indicating its antioxidant capacity and health-enhancing characteristics. Catechin glycosides, particularly C3'G (cyanidin-3-glucoside), exhibit potential as stable catechin precursors (Raab et al., 2010).

The limitations of this study included factors such as method standardization and validation, the flavonoid–antioxidant relationship, the applicability of previous studies, comparability between plant parts, and constraints in sample collection. These limitations are crucial for interpreting and generalizing the study's findings.

Previous studies have reported significant differences in the flavonoid content between different plant parts of both the *B. pseudolongipes* and *B. sasonii* plants. The results of Balos (2021) revealed that the highest amount of flavonoids was observed in the bulb extracted by a traditional extraction method, while the results of Tekin (2022) revealed that the highest content was in the leaf extract, followed by the flower, bulb, and stem extracts.

The results of these studies provide valuable guidance for the effective use of herbal resources and the selection of appropriate plant components for potential therapeutic applications. Combining these results with the current study can assist in the pharmacological evaluation and potential therapeutic applications of *B. pseudolongipes* plants; however, further research is required to understand their biological effects.

4. Conclusion

This study examined the elemental composition and the total phenolic and flavonoid contents in the methanol extract of *B. pseudolongipes* plants. Elemental analyses revealed that the plant is particularly rich in potassium and calcium. Consequently, it is a valuable natural product that could serve as a crucial source for developing novel drugs. This plant is also rich in phenolic compounds, and its high flavonoid content further underscores its high antioxidant capacity. Therefore, it possesses an antioxidant potential that can help protect the body from free radicals. Considering the positive effects of phenolic components on human health, the *B. pseudolongipes* plant holds promise for its utilization in natural resource-based medicines and functional foods. However, further comprehensive studies are required to fully elucidate its potential health benefits. Thus, the *B. pseudolongipes* plant is a valuable natural health resource with promising potential for application in human nutrition and health.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	İ.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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AN IMPROVED HYBRID MODEL BASED ON ENSEMBLE FEATURES AND REGULARIZATION SELECTION FOR CLASSIFICATION

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Abstract: Feature selection is a pivotal process in machine learning, essential for enhancing model performance by reducing dimensionality, improving generalization, and mitigating overfitting. By eliminating irrelevant or redundant features, simpler and more interpretable models are achieved, which generally perform better. In this study, we introduce an advanced hybrid method combining ensemble feature selection and regularization techniques, designed to optimize model accuracy while significantly reducing the number of features required. Applied to a customer satisfaction dataset, our method was first tested without feature selection, where the model achieved a ROC AUC value of 0.946 on the test set using all 369 features. However, after applying our proposed feature selection method, the model achieved a higher ROC AUC value of 0.954, utilizing only 12 key features and completing the task in approximately 43% less time. These findings demonstrate the effectiveness of our approach in producing a more efficient and superior-performing model.

Keywords: Feature selection, Basic filter method, Regularization, Logistic regularization, Tree based feature selection

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1. Introduction

Feature selection is an essential step in machine learning, aimed at selecting the most relevant features from a dataset to enhance model performance (Miao and Niu, 2016). By reducing the number of features, it simplifies the learning process, speeds up computation, and improves model interpretability. This process also helps prevent overfitting, especially in high-dimensional datasets, by eliminating irrelevant or redundant features that add noise. As a result, models become more efficient and capable of generalizing better to unseen data, striking a balance between complexity and accuracy (Shardlow, 2016). Ultimately, feature selection enables more robust, interpretable, and scalable machine learning models (Li et al., 2017).

When feature selection is not implemented, several problems arise. First, irrelevant and unnecessary features introduce noise into the model, making it difficult for the algorithm to focus on truly important patterns in the data. This can lead to overfitting, where the model becomes too specific to the training data and performs poorly on unseen data. Additionally, adding unnecessary features increases computational costs, slowing down model training and inference (Kalousis et al., 2007; Sugiyama, 2015). In real-world applications, especially with large datasets, this can lead to inefficiency, wasted resources, and difficult-to-interpret models. Without feature selection, it becomes more difficult to understand which features contribute most to the model's predictions, reducing confidence and explainability in critical applications (Remeseiro and Bolon-Canedo, 2019; Luftensteiner et al., 2021).

In this paper, we introduce an enhanced hybrid model method that integrates ensemble feature selection with regularization techniques, designed to optimize feature selection for machine learning models. Our approach effectively balances model complexity and accuracy by leveraging regularization to penalize the inclusion of irrelevant features. This strategy ensures that only the most critical features are retained, thereby improving model performance and reducing computational time. In our experiments with a customer satisfaction dataset, our method achieved superior performance, attaining a ROC AUC of 0.954 using just 12 features, compared to a ROC AUC of 0.946 with the full set of 369 features. Additionally, the process was completed in approximately 43% less time, demonstrating that our approach simplifies the model and accelerates computation without compromising on performance.

This paper makes the following contributions:

- Our proposed method outperformed models using all 369 features by achieving better accuracy with just 12

selected features, resulting in a simpler and more efficient model.

- When applied to the customer satisfaction dataset, our proposed feature selection method reduced the computation time by 43%, demonstrating significantly faster performance compared to methods that do not use feature selection.
- We introduce an enhanced hybrid model method that integrates ensemble feature selection with regularization techniques, effectively reducing dimensionality while maintaining or improving model performance.
- We provide an empirical evaluation of the trade-offs between feature reduction and model accuracy, offering insights into the balance between complexity and computational efficiency.

The paper is structured as follows: Material and Methods outlines the proposed hybrid ensemble and regularization feature selection method, detailing its mathematical foundation, advantages, and the dataset used in the study. This section also explains the preprocessing steps and the machine learning algorithms employed to evaluate the method. Results present a comparative analysis of model performance, both with and without feature selection, highlighting improvements in accuracy and reductions in computational time. Finally, the Conclusion summarizes the key findings, emphasizes the efficiency of the proposed method, and suggests directions for future research.

2. Materials and Methods

2.1. Feature Selection

Feature selection is an important technique in machine learning that improves model performance by focusing on the most relevant features and discarding irrelevant or redundant ones. This process helps simplify models, improve accuracy, and reduce computational overhead. In high-dimensional datasets where many features may contribute little to model performance, feature selection is vital to reduce overfitting and improve generalization (Ramchandran and Sangaiah, 2018). Figure 1 illustrates this concept by showing how irrelevant features are removed and important features are retained, and highlights the process of refining the feature set to optimize model efficiency. The figure provides a clear visual representation of how feature selection streamlines the data and ultimately leads to more efficient and accurate predictive models (Jimenez-del-Toro et al., 2017; Yousefi and Aktaş, 2024).

Figure 1. Feature selection process.

Feature selection commonly employs methods such as wrapper (Kohavi and John, 1997), filter (Chandrashekar and Sahin, 2014), embedded (Zheng and Casari, 2018), ensemble (Opitz and Maclin, 1999), and hybrid (Kabir et al., 2010) approaches to evaluate feature importance and enhance model performance. Before applying these advanced methods, it's crucial to use basic filter techniques to clean the dataset (Moldovan et al., 2017). Methods like constant features, quasi-constant features, duplicated features, and highly correlated feature removal are employed to eliminate low-information or redundant features. These preliminary filtering steps ensure a cleaner, more relevant feature space, setting the stage for more effective and comprehensive feature selection, and ultimately improving model generalization (Yousefi and Aktaş, 2024).

2.2. Basic Filter Methods

Feature selection is an essential step in machine learning and data analysis, ensuring that only the most relevant features are utilized in predictive models. The process usually begins with basic filter-based techniques, which help detect and remove irrelevant or redundant features from the dataset. As shown in Figure 2, four commonly used filter-based methods include constant feature removal, quasi-constant feature removal, duplicated feature elimination, and highly correlated feature detection. These methods streamline the feature selection process, leading to more efficient and higher-performing models (Yousefi and Varlıklar, 2024).

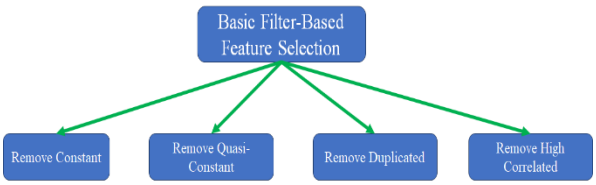

Figure 2. Basic filter-based feature selection methods.

- Constant Feature Removal: This approach focuses on identifying features that maintain a constant value across all data instances. Since these features contribute little or no useful information to predictive modelling, they can be safely discarded. Removing constant features helps reduce the dimensionality of the dataset, making the subsequent analysis and model-building steps more efficient and streamlined.
- Quasi-Constant Feature Removal: Quasi-constant features show very little variation across instances, offering limited value for predictive modeling. Although not completely constant, their low variance makes them ineffective in differentiating between classes or outcomes. Detecting and removing quasi-constant features helps to enhance the overall quality of the feature space by eliminating features that do not contribute meaningfully to the model's performance.
- Duplicated Feature Removal: Duplicated features are those that are nearly identical or highly similar to one another, adding unnecessary redundancy to the dataset. These features can increase complexity and potentially lead to bias or overfitting in machine learning models. Removing duplicated features helps streamline the

feature space, making the dataset more manageable and improving the robustness and reliability of further analysis.

- Highly Correlated Feature Removal: Highly correlated features are features that exhibit a strong linear relationship with each other and provide similar information to the model. Including such features can create redundancy and negatively impact the model by increasing its complexity and increasing the risk of multicollinearity. Identifying and removing highly correlated features helps simplify the feature space, reduce overfitting, and improve the overall performance and interpretability of the model.

2.3. Regularization

Regularization is a crucial technique in machine learning used to prevent overfitting, especially in models with high complexity. Overfitting occurs when a model captures noise and patterns specific to the training data, resulting in poor generalization to unseen data. Regularization techniques add a penalty to the model's loss function, discouraging it from fitting too closely to the training data and promoting a simpler, more general model that performs well on new data (Tian and Zhang, 2022).

In the context of regression models, regularization modifies the cost function by adding a penalty term that controls the magnitude of the model's parameters (weights). The most commonly used regularization techniques are L1 regularization (Lasso) (Ranstam and Cook, 2018; Tibshirani, 1996) and L2 regularization (Ridge) (McDonald, 2009; Hoerl and Kennard, 1970), both of which are applied in linear and logistic regression models to enhance their robustness.

Logistic regression is a classification algorithm used to estimate the probability of a binary outcome (Kleinbaum et al., 2002; Hosmer et al., 2013). Regularization is important in logistic regression to prevent the model from becoming too complex, especially when dealing with high-dimensional data. In logistic regression, the regularization term is added to the loss function, which is the log-likelihood of the model (Salehi et al., 2019). The regularized cost function for logistic regression can be expressed as in equation 1.

$$j(\theta) = -\frac{1}{m}\sum_{i=1}^{m}\left[y^{(i)}\log(h_\theta(x^{(i)})) + (1 - y^{(i)})\log(1 - h_\theta(x^{(i)}))\right] + \lambda\sum_{j=1}^{n} R(\theta_j) \quad (1)$$

Where $j(\theta)$ is the regularized cost function, m is the number of training examples, $y^{(i)}$ is the actual class label for the i^{th} training example, $h_\theta(x^{(i)})$ is the predicted probability of the class, λ is the regularization parameter, and $R(\theta_j)$ is the regularization term, which could be L1 (Lasso) or L2 (Ridge).

The regularization term $R(\theta_j)$ helps control the magnitude of the model parameters, ensuring that the model does not overfit to the training data. In the L1 configuration, the penalty term is the absolute value of the coefficients and is given by equation 2:

$$R(\theta_j) = \sum_{j=1}^{n}|\theta_j| \quad (2)$$

In the L2 configuration, the penalty is the squared value of the coefficients and is as in equation 3:

$$R(\theta_j) = \sum_{j=1}^{n}\theta_j^2 \quad (3)$$

2.4. Tree Based Feature Selection

Tree-based feature selection is a powerful method in machine learning used to identify the most important features within a dataset (Freeman et al., 2013). This approach leverages decision trees or ensembles of trees, such as Random Forest, to rank features based on their contribution to the predictive model. In tree-based methods, the importance of a feature is determined by how often and how effectively it is used to split the data across all trees in the ensemble. Features that result in the greatest reduction in impurity or increase in information gain are ranked higher (Azhagusundari and Thanamani, 2013). The feature importance score for a given feature f_i can be mathematically expressed as in equation 4 (Zhou et al., 2021):

$$\text{Importance}(f_i) = \sum_{t\in\text{trees}}\frac{\Delta\text{Impurity}(f_i, t)}{\text{Number of Trees}} \quad (4)$$

where $\Delta\text{Impurity}(f_i, t)$ represents the decrease in impurity caused by feature f_i in tree t.

In our study, we employed the Random Forest algorithm (Liaw and Wiener, 2002), a widely used ensemble method for tree-based feature selection (Hasan et al., 2016). Random Forest constructs multiple decision trees during training and aggregates their predictions to improve accuracy and reduce overfitting (Biau and Scornet, 2016). The feature importance score provided by Random Forest highlights the contribution of each feature to the model's predictive power. By focusing on these scores, we were able to streamline our model by selecting only the most critical features. This approach demonstrated the effectiveness of tree-based feature selection, particularly with Random Forest, in simplifying models while maintaining or even enhancing their accuracy and robustness. The importance of a feature in the Random Forest is calculated by averaging the reduction in impurity across all trees, as described by the formula above. This process ensures that only the most influential features are retained, leading to a more efficient and interpretable model (Menze et al., 2009).

2.5. Proposed Method

Feature selection plays a crucial role in machine learning and data analysis by enhancing model performance

through the identification and selection of the most relevant features from a dataset. This process focuses on removing redundant, irrelevant, or noisy features, which helps reduce model complexity, mitigate overfitting, and improve computational efficiency. The primary objective is to concentrate on the most informative features that significantly boost the model's predictive accuracy (Li et al., 2017).

In this study, we propose an advanced hybrid approach that combines ensemble feature methods with regularization techniques to optimize both feature selection and model performance. Our proposed method demonstrates superior efficiency, achieving better results in less time with fewer features compared to traditional methods.

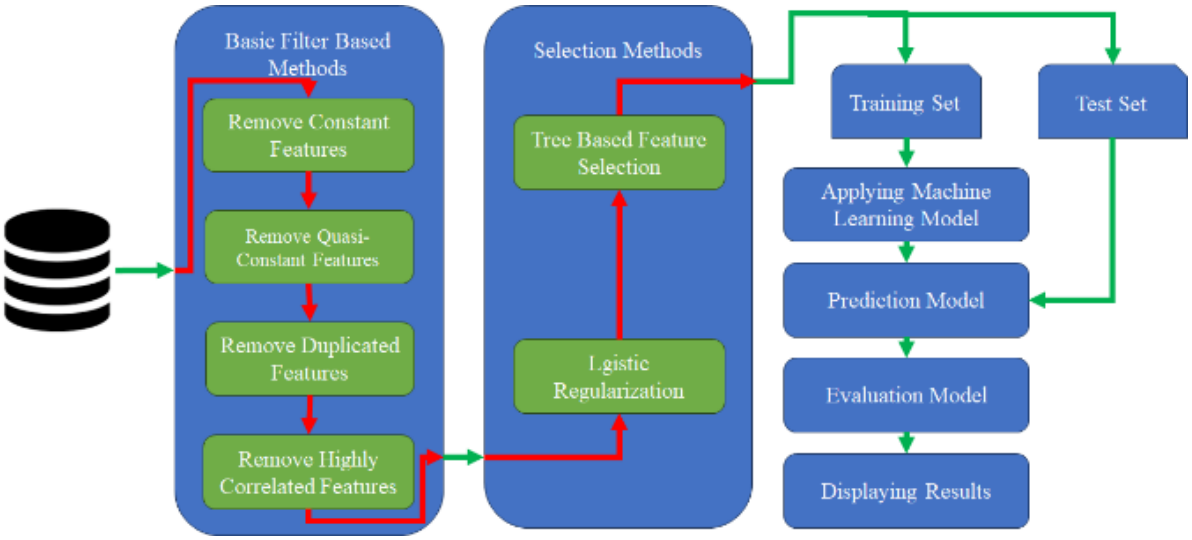

Figure 3. Proposed method.

In our proposed approach, the process begins with the application of basic filter-based feature selection methods, as depicted in Figure 3. The initial phase involves removing features with zero variance, which are features where all values are identical. These features are discarded because they lack informative value for the model. This initial removal can be mathematically described by equation 5:

$$X_{clean} = X - \{x_j | \, Var(x_j) = 0\} \quad (5)$$

Here, X denotes the original dataset, and X_{clean} represents the dataset after removing constant features. In the second stage, features with low variance, which could potentially impact model performance, are removed based on a predefined variance threshold, as shown in equation 6. For our study, this threshold was set to 0.998.

$$X_{clean} = X_{clean} - \{x_j | \, Var(x_j) < \tau\} \quad (6)$$

where τ is a specified variance threshold.

In the third stage, features carrying the same or nearly the same information are removed to reduce redundancy. This is done by comparing the features for exact copies as in equation 7:

$$X_{clean} = X_{clean} - \{x_j | \, \exists x_i \text{ suhc that } x_i = x_j \text{ and } j \neq i\} \quad (7)$$

Here, X_{clean} represents the dataset after removing duplicate features, and x_i=x_j denotes features that are identical.

The final stage of feature selection involves using a simple filter to eliminate highly correlated variables. In this stage, only one feature is retained from among those with strong correlations to minimize model complexity and enhance generalization. This process is mathematically represented by equation 8:

$$X_{selected} = \{x_j | \, Corr(x_j, x_i) < p_{max})\} \quad (8)$$

Here p_{max} represents the maximum correlation threshold, which was determined as 80% in our study.

In this section, as illustrated in Figure 3, we first apply logistic regularization within the selection methods. Techniques such as L1 and L2 regularization are employed in logistic regression models to decrease model complexity and mitigate overfitting. The mathematical representation of the regularization term is given by equation 9:

$$j(\theta) = -\frac{1}{m}\sum_{i=1}^{m}\left[y^{(i)} \log(h_\theta(x^{(i)})) + (1 - y^{(i)}) \log(1 - h_\theta(x^{(i)}))\right] + \lambda \sum_{j=1}^{n} w_j^2 \quad (9)$$

Where $j(\theta)$ denotes the regularized cost function, m represents the number of training examples, $y^{(i)}$ is the

actual class label for the i^{th} training example, $h_\theta(x^{(i)})$ is the predicted probability of the class, λ is the regularization coefficient, and the L2 penalty term $\lambda \sum_{j=1}^{n} w_j^2$ plays a crucial role in managing the magnitude of the coefficients, thereby helping to prevent overfitting.

In the last stage of the selection method, we applied tree-based feature selection. Features were ranked based on their importance using methods like decision trees. A key metric for assessing feature importance in decision trees is Information Gain. This measure evaluates the reduction in entropy (uncertainty) achieved by a feature, helping to identify those that offer the greatest amount of information about the target variable. The Information Gain for feature x_j can be calculated as equation 10:

$$\text{Information Gain}\left(x_j\right) = \text{Entropy}\,(S) - \sum_{v \in \text{Values}(x_j)} \frac{|S_v|}{|S|} \text{Entropy}(S_v) \quad (10)$$

Where Entropy(S) is the entropy of the original dataset S, $\text{Values}\left(x_j\right)$ are the distinct values of the feature x_j, $|S_v|$ is the number of instances in subset S_v corresponding to each value v of x_j, and $\text{Entropy}(S_v)$ is the entropy of the subset S_v.

The entropy of a dataset S can be calculated as equation 11:

$$\text{Entropy}\,(S) = -\sum_{k=1}^{K} p_k \log_2(p_k) \quad (11)$$

where p_k is the probability of each class k in the dataset and K is the number of classes.

Finally, after splitting the data into training and test sets, we build the machine learning model using the Random Forest algorithm. We then proceed with the estimation process and evaluate the model to measure its performance. The results are presented to show how well the model has performed.

2.6. Experiments

2.6.1. Dataset

The dataset, accessible via the provided link, provides detailed insights into the satisfaction levels of Santander Bank customers. It is an important resource for analyzing customer experiences and preferences in the banking sector. The dataset contains 369 features, providing a comprehensive view of various aspects that affect customer satisfaction.

In this study, we did not initially select any features and then applied the proposed method to this dataset. The results and implications of this approach are discussed in the results section of our study. For those who want to explore the dataset further, it is freely available on Kaggle via the following link:

https://www.kaggle.com/competitions/santander-customer-satisfaction/data

2.6.2. Evaluation metrics

Evaluation metrics are essential for assessing machine learning model performance, offering quantitative measures to gauge how well a model is performing and to compare different models. In our study, Accuracy, Precision, Recall, F1 Score, ROC AUC Score, and R^2—were employed to evaluate and compare the performance of our model, ensuring a comprehensive assessment of its effectiveness (Hossin and Sulaiman, 2015).

Accuracy measures the proportion of correctly classified instances out of the total. It is given by $\frac{TP+TN}{TP+TN+FP+FN}$ where TP, TN, FP, and FN stand for True Positives, True Negatives, False Positives, and False Negatives, respectively.

Precision assesses the proportion of true positive predictions among all positive predictions, calculated as $\frac{TP}{TP+FP}$.

Recall evaluates the proportion of true positive predictions among all actual positive instances, represented as $\frac{TP}{TP+FN}$.

F1 Score provides a balanced measure between Precision and Recall, computed as $2 * \frac{Precision*Recall}{Precision+Recall}$.

ROC AUC Score measures the area under the Receiver Operating Characteristic curve, which plots the true positive rate against the false positive rate at various thresholds.

R^2 used in regression, indicates the proportion of variance in the dependent variable explained by the independent variables, calculated as $1 - \frac{SS_{res}}{SS_{tot}}$, SS_{res} is Residual Sum of Squares, and SS_{tot} is Total Sum of Squares.

Confusion Matrix summarizes the number of correct and incorrect predictions across classes, showing True Positives, True Negatives, False Positives, and False Negatives.

3. Results and Discussion

In this study, we highlight the importance of feature selection in machine learning, emphasizing its role in improving model performance by reducing complexity, preventing overfitting, and increasing computational efficiency. Feature selection allows us to focus on the most relevant and informative features, which is crucial for building effective models.

Our proposed method has shown that the model can achieve better performance in less time by using fewer features. This is especially important in practical applications where computational resources and time are limited. The results clearly show that when the model is trained with selected features, it not only reduces the overall training time but also improves the prediction accuracy.

To illustrate the impact of feature selection, we present the results in two ways. First, we show the model's performance using all 369 features without any feature selection. The results indicate that while the model performs adequately, it is not optimized in terms of time

and complexity. Second, we apply our proposed feature selection method, and the results reveal a significant improvement in performance, with the model achieving higher accuracy and efficiency using a reduced set of features.

In the first stage, we performed the prediction process using the Random Forest algorithm without applying any feature selection method, utilizing all 369 features. As shown in Table 1, this approach yielded an accuracy of 0.946, and the results were obtained in approximately 546 seconds.

Table 1. Results of the model without using feature selection

Accuracy	R^2	F1	Recall
0.946	0.946	0.947	0.952
Precision	ROC_AUC	Time	Feature
0.944	0.946	564s	369

Note: All results are from the test dataset.

As illustrated in Figure 4, the confusion matrix was generated, which provides a detailed breakdown of the model's performance across different classes. The matrix highlights the number of true positives, true negatives, false positives, and false negatives, giving us insight into the model's strengths and areas for improvement.

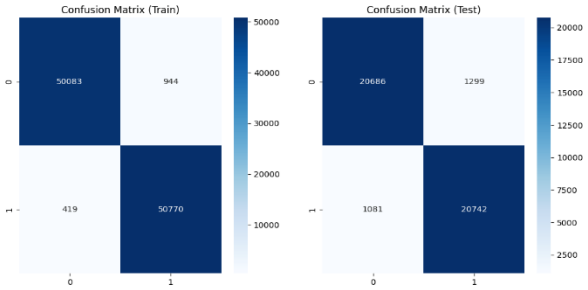

Figure 4. Confusion matrix of random forest model without using the proposed method.

In Figure 5, we can observe the ROC AUC curve, which demonstrates the model's performance when all features are used. The ROC AUC score achieved was 0.946, indicating a strong ability of the model to discriminate between the classes.

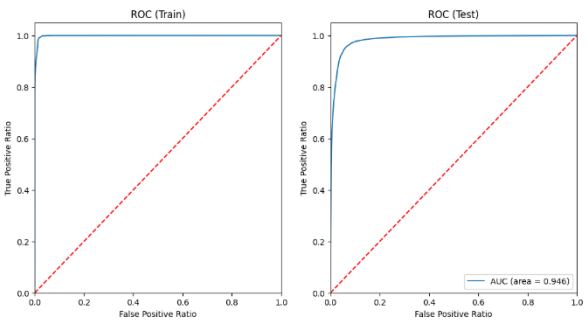

Figure 5. ROC_AUC graph of random forest model without using the proposed method.

In the second stage, following the application of the simple filter feature selection method outlined in this article, we applied logistic regularization and subsequently selected the most relevant features using ensemble methods. As shown in Table 2, this approach allowed us to achieve an accuracy of 0.954 using just 12 features instead of the original 369. This resulted in not only improved performance but also a significant reduction in processing time. Our proposed method reached the outcome in 327 seconds, which is 43% faster than the previous approach.

Table 2. Results of the model using the proposed method

Accuracy	R^2	F1	Recall
0.954	0.954	0.954	0.952
Precision	ROC_AUC	Time	Feature
0.958	0.954	327s	12

Not: All results are from the test dataset.

Figure 6 presents a confusion matrix that details the model's performance across various classes. It highlights the counts of true positives, true negatives, false positives, and false negatives, demonstrating that the model shows improved performance compared to the previous one.

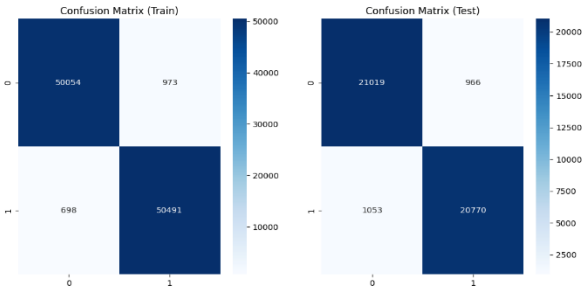

Figure 6. Confusion matrix of the proposed method.

Figure 7 illustrates the ROC AUC curve for the model that was trained using just 12 features. The ROC AUC score of 0.954 reflects the model's strong performance with the reduced feature set. This high score confirms that our proposed method is effective in maintaining predictive accuracy while simplifying the feature set.

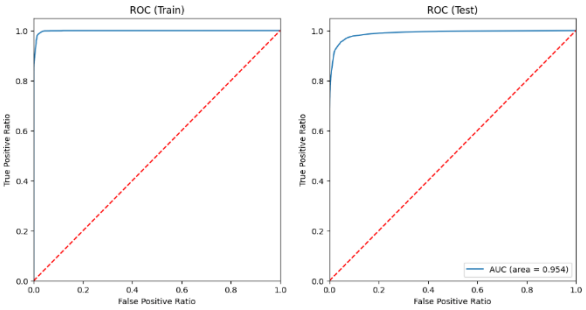

Figure 7. ROC_AUC graph of the proposed method.

4. Conclusion

Feature selection plays a crucial role in the development of efficient and accurate machine learning models. By identifying and retaining the most relevant features, feature selection helps reduce model complexity, prevent overfitting, and improve computational efficiency. It ensures that the model focuses on the most informative aspects of the data, leading to better generalization and more reliable predictions.

In this study, we proposed a hybrid feature selection method that combines simple filter techniques with logistic regularization and ensemble methods. This approach was designed to optimize both the performance and efficiency of the model. When we applied the Random Forest algorithm to the customer satisfaction dataset without any feature selection, using all 369 features, we achieved an ROC AUC score of 0.946. However, by implementing our proposed feature selection method, we improved this score to 0.954 while drastically reducing the number of features to just 12. Additionally, the processing time was reduced by 43%, highlighting the efficiency gains of our method.

The significant improvements in both accuracy and processing time underscore the advantages of our proposed feature selection method. By eliminating redundant and less informative features, the model not only becomes more efficient but also delivers superior performance. This demonstrates the effectiveness of the method in handling large datasets, making it a valuable tool for similar applications in other domains.

Looking ahead, we believe that further optimization of the regularization parameters through the use of metaheuristic algorithms could yield even better results. Future work will focus on exploring this approach to enhance the model's performance. By fine-tuning these parameters more precisely, we aim to achieve even greater accuracy and efficiency in subsequent studies.

Author Contributions

The percentages of the authors' contributions are presented below. The authors reviewed and approved the final version of the manuscript.

	T.Y.	Ö.V.	M.S.O.
C	45	35	20
D	45	35	20
S	45	35	20
DCP	45	35	20
DAI	45	35	20
L	45	35	20
W	45	35	20
CR	45	35	20
SR	45	35	20
PM	45	35	20
FA	45	35	20

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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HAZARD IDENTICATION OF WELL TEST OPERATION IN DRILLING AND PRODUCTION OFFSHORE PLATFORM BY HAZID

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Abstract: A significant portion of energy resources has been discovered in offshore sectors, leading to a steadily increase in the volume of activities and operations. Once a well is drilled and fluid extraction begins, all the reservoir parameters, start to change. well test operation is one of the most crucial tools for engineers to comprehend the behavior and parameters of hydrocarbon reservoirs. In this study, the hazards associated with the well test operations has been identified by using HAZID technique. A total of 189 risks were identified in the initial risk assessment, with 35 categorized as low risk, 88 as medium risk, and 66 as high risk. Following the implementation of protection layers in the secondary risk assessment, the number of low risks incidents increased, while medium and high-risk incidents saw a significant reduction. Most of the identified risks are associated with loading operations and sea transportation from the port to the drilling rig. Since loading and unloading operations are critical and frequently occurring tasks in well testing, they contribute significantly to the overall risk profile.

Keywords: Hazard identification, HAZID, Offshore, Risk, Well test

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1. Introduction

Every task carries some potential risk to health or injury. The only way to fully eliminate this risk is to refrain from performing the task entirely. However, this is rarely a practical solution. In many cases, it is reasonable to proceed with a hazardous task if the risk can be minimized. Risk management involves identifying hazards, assessing the level of risk, and implementing controls to reduce that risk to acceptable levels (Nardone, 2011). The importance of offshore drilling is clear, particularly given the growing demand for these resources. Offshore drilling in developing and underdeveloped countries is particularly associated with numerous hazards, which hinder the implementation and effectiveness of these operations. As a result, these hazards can negatively impact the economies of countries.it is crucial to implement measures and policies to mitigate these risks (Yu and Michael, 2019). Once a well is drilled and fluid extraction begins, key reservoir parameters such as pressure, fluid volume, fluid viscosity, and other vital characteristics of the well begin to change. Well testing is the analysis of reservoir and well behavior over time, and the results obtained from these tests can greatly impact the determination of the actual reservoir parameter values. Well test interpretation entails extracting insights about a reservoir by analyzing the pressure-transient response caused by a change in production rate. These insights are then used to support reservoir management decisions. (Spivey and Lee, 2013). The well's behavior is usually monitored over a relatively short time frame, depending on the test's objectives, compared to the reservoir's overall lifespan. For well evaluation, tests are often completed within two days or less. However, reservoir limit testing may require several months of pressure data to be gathered (Bourdet, 2002). In a well testing operation, surface equipment links an active, high-pressure, high-temperature hydrocarbon well to burners set up on a jack-up rig. This setup is used to produce gas at various flow rates (Nardone, 2011). A well test presents several challenges due to its complexity, involving a wide range of tasks carried out by a diverse group of contractors and employees. This operation requires precise coordination, expertise, and attention to detail to ensure its success and safety. Many of the tasks are inherently hazardous and relate to pressure, flammable liquids and gases, explosives, toxic chemicals, working at heights, confined spaces, noise, heat stress, lifting, trips and falls, and manual handling. The complexity of the operation necessitates a structured approach to safety management, ensuring that risks are systematically identified, evaluated, and mitigated throughout the entire process.

Despite its cruciality, numerous studies have pointed out that worker safety in the offshore drilling industry is frequently neglected (Durell and Neff, 2019).

As a primary step of safety management, comprehensive hazard identification plays a crucial role in ensuring safety by helping to recognize potential risks early in the operation, allowing for proactive measures to mitigate them. The objective of this study is to identify the hazards associated with clean-up and surface well testing equipment in an offshore gas development plan, utilizing the Hazard Identification (HAZID) methodology.

2. Materials and Methods

In this research, the HAZID methodology was employed to detect and assess hazards. This approach, created by SHELL International Company, is designed to identify risks in the offshore hydrocarbon sector (Shell international Exploration and Production, 1995). The HAZID study conducted is a combined approach, integrating both conceptual and detailed HAZID methods. The identification of hazards and risks related to the operation has been done in a qualitative way by using experts' opinion through brainstorming.

2.1. Research Area

The offshore platform in the Persian Gulf, comprising 12 wells, is capable of producing up to 56 million cubic meters of sour gas daily, both at maximum and sustained levels, from the offshore reserves of the shared gas field.

2.2. Hazard Identification Technique (HAZID)

The HAZID technique is a method for identifying hazards and threats, involving a meeting with a highly experienced, multidisciplinary team. The team utilizes a structured brainstorming approach, guided by a checklist of possible health and safety concerns, to evaluate the relevance of potential hazards. The primary advantage of HAZID is that the early detection and evaluation of significant health, safety, and environmental hazards offer crucial insights for project development decisions. This process helps ensure safer and more cost-effective design choices are implemented (Shell international Exploration and Production, 1995). HAZID is a widely and frequently used technique in the petroleum industry. It is often applied across a broad range of areas, projects, and operations (Crawley, 2020).

Prior to initiating the study, the research methodology was outlined in detail to clarify the work steps, as illustrated in Figure 1. The HAZID technique used in this study consists of 2 main steps which are as follow.

2.2.1. Step (1): Planning step

This step consists of team building, planning meetings and preparing required documentation.

The initial step is to assemble a team with the necessary expertise for the specific study. Choosing the right team is just as crucial as the framework itself. The key to a successful HAZID lies in achieving the right balance of breadth and depth in the team's experience. When forming the study team, all relevant and active expertise in well testing operations was selected. The team assembled for the HAZID Study is presented in Table 1. Once the HAZID team was formed, eight meetings (Table 2) were conducted to perform the research studies.

The total duration of these meetings exceeded 18 hours.

All the required documents for the HAZID studies were determined in the first meeting. These documents are generally: Surface clean-up and well testing operation procedure, last hazard identification and risk assessment, incident report (accident and near miss report), well testing equipment specification, safe operation procedures, certifications, layouts, hydrocarbon fluid composition report and so on.

In the following section, the well testing operation was meticulously divided into its component tasks, with the operation stages being separately outlined. Next, the operation details were discussed, and the scope of the studies was defined. In order to more accurately identify hazards and evaluate risks, the clean-up and surface well testing were treated as a single system, which was then broken down into key sub-systems. To identify and assess risks in the clean-up and well test operation, all operational processes were thoroughly examined. After discussions, reviews, and reaching a consensus, six study nodes were chosen based on the main stages of the operation to investigate and identify potential hazards. Subsequently, each of the selected nodes is divided into study subgroups, allowing for a more detailed and focused examination of the hazards associated with every aspect of the operation. Table 3 illustrates the study nodes. All phases of the operation, categorized into 18 study sub-nodes, were thoroughly analyzed using the brainstorming method. This involved the exchange of insights, opinions, and experiences from experts, along with the application of the HAZID checklist from Shell company's guidelines (Shell international Exploration and Production, 1995). The checklist is divided into four main sections as follow, enabling a comprehensive and systematic assessment of various types of risks.

1: External and Environmental Hazards Check list,
2: Facility Hazards Check List,
3: Health Hazards Check List,
4: Project Implementation Issues Check List.

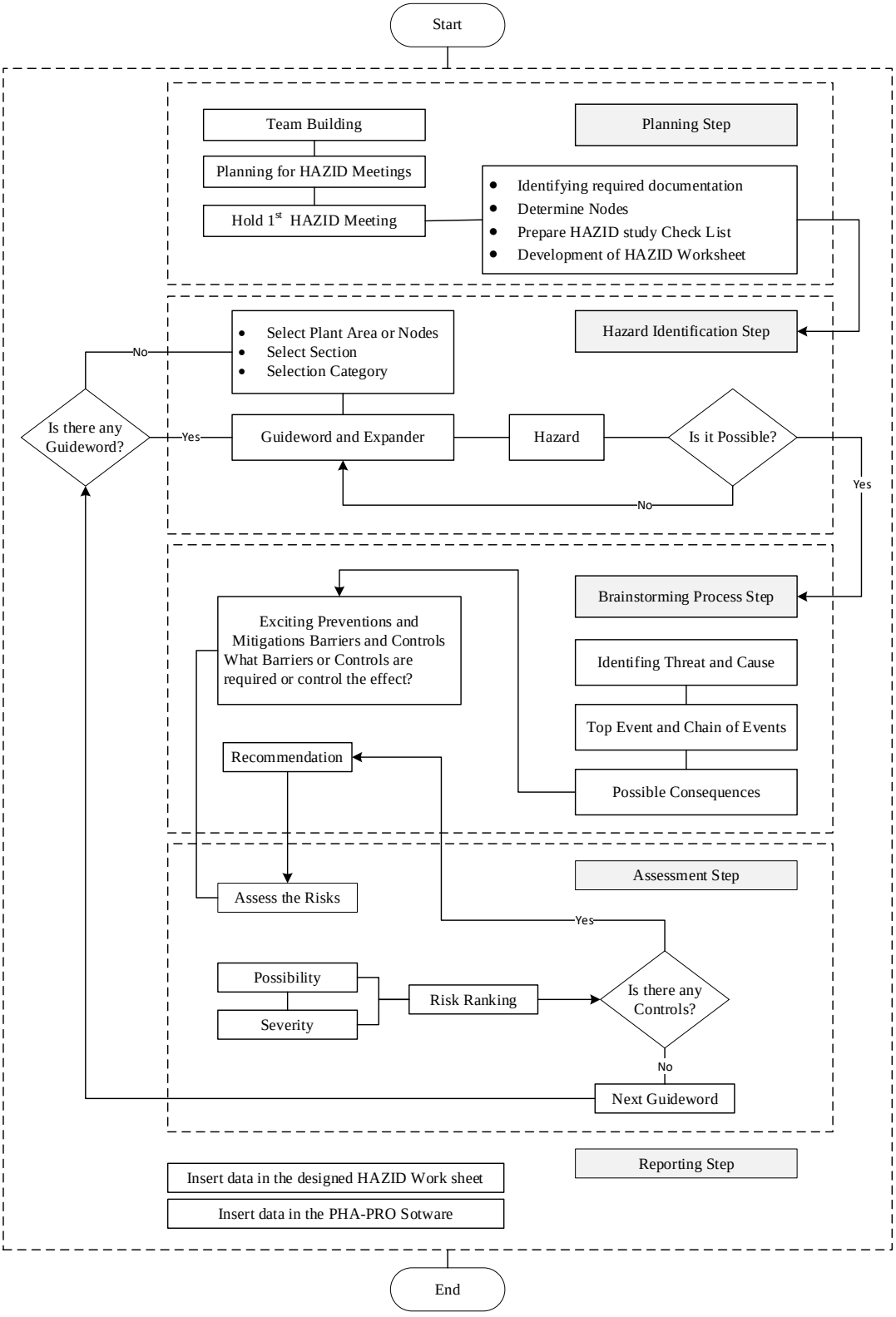


Figure 1. Research HAZID study methodology.

Table 1. Surface well test operation HAZID study assembling team

No.	Age	Experience	Educational Field Study	Education Degree	Organization Title	Rank
E1	42	20	Drilling Engineering	Master	Drilling Eng.	Manager
E2	38	15	Petroleum Engineer	Master	Company Man	Head
E3	45	22	HSE Management	Master	HSE Lead	Lead
E4	46	28	Petroleum Engineer	Bachelor	Offshore Installation Manager	Manager
E5	48	22	Mechanical Engineer	Master	Barge Master	Head
E6	48	22	Chemical Engineer	Master	Tool Pusher	Supervisor
E7	46	20	Petroleum Engineer	Bachelor	Field Supervisor	Manager
E8	35	15	Electrical Engineer	Bachelor	Well Test Dat Analysis Engineer	Operator
E9	43	18	Chemical Engineer	Master	Well Test Engineer	Supervisor
FS	25	3	HSE Management	PhD Student	-	-

Table 2. Planning for HAZID meetings

No.	Meeting Agenda	Meeting Minutes	Date	Duration
S-1	Opening Meeting	Discussion Scope of work	20.11.2023	4.30 hr
S-2	Brainstorming Meetings	Hazard Identification in Node No. 01	25.11.2023	2.00 hr
S-3		Hazard Identification in Node No. 02	28.11.2023	2.00 hr
S-4		Hazard Identification in Node No. 03	03.12.2023	2.00 hr
S-5		Hazard Identification in Node No. 04	06.12.2023	2.00 hr
S-6		Hazard Identification in Node No. 05	14.12.2023	2.00 hr
S-7		Hazard Identification in Node No. 06	16.12.2023	2.00 hr
S-8	Closing Meeting	Conclusion	20.12.2023	2.00 hr

Table 3. Node description

Node Number	Node Description
N1	Engineering
N2	Clean-up and Surface Well Test Equipment Logistic Package-Loading
N3	Clean-up and Surface Well Test Equipment Rig-Up (Assembling and installation)
N4	Clean-up and Surface Well Test Operation (Flow and Measurement)
N5	Clean-up and Surface Well Test Equipment Rig Down (De-assembling)
N6	Clean-up and Surface Well Test Equipment Logistic Package-Back Load

2.2.2. Step (2): Hazard identification step

Holding brainstorming meetings, HAZID study team members discussed about identifying hazards in each node as below steps:

•Select the node

•Determine subsystem, main equipment, tools, machinery, software, documents, operation parameters

•Select the section.

•Select category for each section from the check list.

•Select the guideword from the check list.

•Select the expander from the check list.

•Determine top events related to each hazard and chain of events.

•Determine the potential threats and causes.

•Determine the consequences of each cause.

•Determine the protection layers which is exciting against the causes and its consequences.

•Assess the risk ranking (primary stage) using risk matrix as shown in Table 4.

•Agree a recommendation for action or further consideration of the problem.

•Assess the risk ranking (secondary stage).

•Apply the next guideword (relevant to the selected categories).

•Apply the next section until they have all been considered.

Finally, all data and finding information collected and categorized in designed worksheets.

3. Results

Findings related to the number of hazards in each section, as determined by the checklist, are presented in Table 5. Most of identified hazards are in section 2, which focuses on facility-related hazards. Following that, the section addressing external and environmental hazards ranked second.

The summary of the results is presented in Table 6. Finally, Table 7 displays all results related to the number of hazards and risks identified by the study nodes, both before and after accounting for the protection layers. The

hazards identified through HAZID have the potential to cause 52 accidents and result in 189 risks affecting vulnerable elements such as people, the environment, assets, and company reputation. To prevent incidents and reduce their severity, a total of 190 protection layers were recommended. In the initial risk assessment, 35 risks were categorized as low risk, 88 as medium risk, and 66 as high risk. Their respective frequencies are 18% for low risk, 47% for medium risk, and 35% for high risk. The majority of identified risks fall within the medium risk range. High risks are most prevalent in node numbers 2 and 6, respectively. After implementing protection layers in the secondary risk assessment, the number of low-risk incidents increased to 108, medium risk incidents decreased to 79, and high-risk incidents reduced to 2.

Additionally, Figure 2 is provided to better illustrate the situation of the identified risks. the x-axis represents the severity of the event consequences on a scale from 1 to 5, while the y-axis denotes the likelihood of the event occurring, categorized from A to E. The z-axis displays the number of event consequences. This arrangement collectively aids in examining the potential outcomes for each risk area based on specific severity and probability levels.

Table 4. HAZID risk matrix

Severity	Ranking	Consequence Description				Possibility				
		People	Environment	Asset	Reputation	A	B	C	D	E
0	0	No Injury	No effect	No Damage	No Impact	0A	0B	0C	0D	0E
1	1	Slight Injury	Slight Effect	Slight Damage	Slight Impact	1A	1B	1C	1D	1E
2	2	Minor Injury	Minor Effect	Minor Damage	Limited Impact	2A	2B	2C	2D	2E
3	3	Major Injury	Localized Effect	Localized Damage	Considerable Impact	3A	3B	3C	3D	3E
4	4	Single Fatality	Major Effect	Major Damage	National Impact	4A	4B	4C	4D	4E
5	5	Multiple Fatalities	Massive Effect	Extensive Damage	International Impact	5A	5B	5C	5D	5E
Possibility Description						Very Low: Not expected to occur during facility life	Low: Could occur once during facility life	Medium: Has Occurred in industry	High: incident has occurred in Company	Very High: happens several times per year
Possibility						A	B	C	D	E

Table 5. The number of hazards in each section

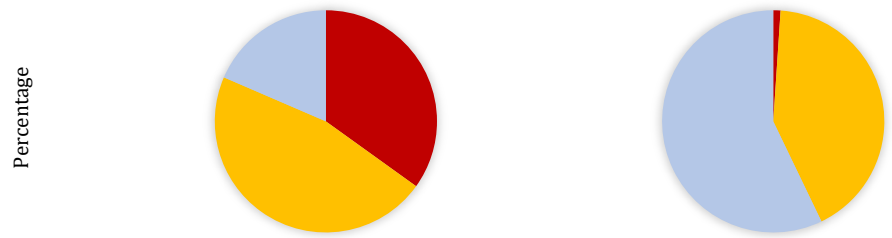
	Section 1	Section 2	Section 3	Section 4
Node.1	0	0	0	1
Node.2	4	3	0	1
Node.3	1	1	0	0
Node.4	0	5	0	0
Node.5	1	1	0	0
Node.6	4	3	0	0

Table 6. Summary table of all study findings

Code	Description	Number of Study Items				
		Event	Causes	Consequences	Safeguards	Recommendations
N1-1	Design and Calculation	2	6	6	8	5
N2-1	Planning / Request	1	1	2	1	1
N2-2	Well Test Equipment Lifting Operation by onshore Crane	8	14	24	23	4
N2-3	Sea Fastening Operation	1	2	6	6	1
N2-4	Sailing	2	3	7	4	1
N2-5	Well Test Equipment Lifting Operation by rig crane	7	14	24	25	9
N3-1	Well Test Equipment Lifting Operation -Rig up operation	3	6	13	13	0
N3-2	Alignment and Make-up of the well test equipment	3	4	7	10	4
N4-1	Pressure Test	2	4	6	5	1
N4-2	Burner Test	1	1	1	2	1
N4-3	Open the well and Flow through separators and burner booms	1	4	16	21	3
N4-4	Sampling (To achieve BSandW)	1	3	6	5	1
N4-5	Emergency Maintenance during operation	1	3	6	5	0
N5-1	Well Test Equipment Lifting Operation - Rig Down	2	3	6	6	0
N6-1	Well Test Equipment Lifting Operation-Back Load	7	13	22	21	0
N6-2	Sea Fastening Operation	1	2	6	6	0
N6-3	Sailing	2	3	7	4	0
N6-4	Well Test Equipment Lifting Operation	7	14	24	25	0

Table 7. Primary and secondary identified risks

Nodes	Primary Risk Assessment			Secondary Risk Assessment			Total
	Low (L)	Medium (M)	High (H)	Low (L)	Medium (M)	High (H)	
1	6	0	0	6	0	0	6
2	9	32	22	34	27	1	63
3	2	7	11	13	7	0	20
4	11	15	9	23	12	0	35
5	1	3	2	2	4	0	6
6	6	31	22	30	28	1	59
Total	35	88	66	108	79	2	189



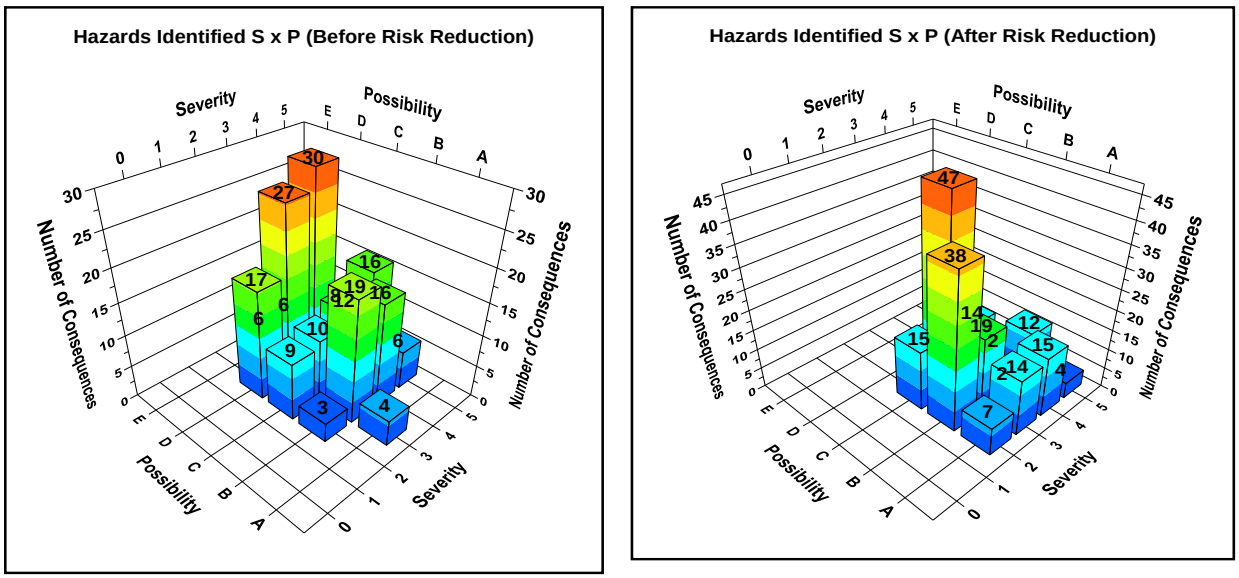


Figure 2. Before and after risk reduction graphics.

4. Discussion

Since there are few studies in the field of offshore operations and HAZID, some additional similar research is mentioned in this part. Rouzhan et al. (2020) in their article highlight that on offshore platforms, one of the primary reasons for hydrocarbon releases is the combination of process upsets and human errors. The results of our study indicate that more than 10% of the causes of high risks are attributed to human errors. Zhong et al. (2020) highlighted in their article on the risk assessment of gas well testing in the South China Sea that the process is highly challenging, costly, and risky. They identified 42 potential risk factors and used fault tree analysis to effectively mitigate these risks. These risk factors are consistent with the causes identified in our research result.

Aliev (2019) explored various hazards linked to offshore drilling, including chemical, physical, biological, ergonomic, and psychosocial risks, all of which may be influenced by the nature of the work or its offshore location. The study recommends a noise control subsystem that can significantly reduce the connection between accidents and factors such as the driller's health, fatigue, and qualifications. An analysis of the risks identified by HAZID reveals that human errors play a significant role in causing accidents. Implementing well-planned systems to improve employee health can be instrumental in reducing accident rates.

In other hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station, Nakayama et al (2016) find 314 accident scenarios by using HAZID. Kim et al. (2015) as a consequence of HAZID and post-HAZID processing, a total of 80 hazards (or hazardous scenarios) were identified, of which 31 hazards (approximately 39%) were deemed significant enough to warrant further consideration. The results of these studies are in line with our findings.

Deling Wang et al. (2023) combines historical accident cases from offshore platforms, analyzes them, and summarizes the risk factors impacting safety management by employing risk matrix analysis. They outlined the safety management measures that can be implemented for the associated risks in the operational process, based on the evaluated results of the risk factors, from four perspectives: environment, equipment, personnel, and management. In the HAZID method, the general classification of risks consists of four categories that align with the identified factors influencing accident occurrences in this study. In fact, this issue demonstrates that the study results align with the framework of the HAZID method, indicating that the HAZID method is a suitable approach for identifying offshore hazards to enhance safety management.

Brandsæter (2002) in his paper discusses the application and utilization of risk assessment in the offshore industry concerning safety aspects. The primary focus of this study is on quantitative risk assessments (QRA). It is noted that the consequence assessment in an offshore QRA typically addresses the following types of accidents: process accidents, riser and pipeline incidents, blowouts, dropped objects, ship collisions, and extreme weather events and earthquakes. In our HAZID study, weather conditions have been recognized as a significant factor contributing to the increased rate of accidents and according to the results, weather conditions and equipment transfer operations are high-risk activities, with the highest number of identified risks in the region related to transfers that can be significantly impacted by weather conditions.

Gunter et al. (2013) found that from 2003 to 2010, offshore transportation incidents were the main cause of worker fatalities in offshore oil and gas operations in the United States. Our results clearly indicate that the majority of high risks are associated with loading operations.

Abdussamie et al. (2018) analyzed the system of a submersible barge using the HAZID technique to determine the worst-case scenarios. They split the submersible barge into eight nodes, which are anticipated to be evaluated during the load-out and launching phases. Same as our study, review of nodes focused on the significance of potential hazards/failure modes in each operation. The hazards identified are quite similar to those identified in the loading operations in this study. Additionally, they note that the risks become tolerable once all reasonably practicable measures have been taken to mitigate them. After identifying the risks, expert opinions were consulted to define practical recommendations and establish necessary preventive layers in this study.

The results of this study can be utilized to conduct broader risk assessments using methods such as HAZOP, FTA, ETA, BOWTIE and so on. One of the most significant and widely used applications of HAZID results is in the Bowtie method. In this technique, the outcomes of the HAZID study are employed to prepare the major accident hazard identification.

Risks identified by the HAZID method in the red range, which have very high financial and life-threating consequences, are classified as major accident hazards. By identifying the threats, events, and protective layers revealed by the HAZID technique, a Bowtie diagram can be developed. Subsequently, critical activities and critical equipment are identified, and a performance standard is established for each.

5. Conclusion

Consequently, HAZID studies are crucial as they serve as the foundational basis for hazard identification and risk assessment in offshore industries. It is important that the risks arising from the routine operation of an offshore facility should be properly identified and managed through a standard formal safety assessment (Shouman et al.2021). Among the 189 identified risks, the majority are associated with nodes 2 and 6, which pertain to loading operations and sea transportation from the port to the drilling rig. Loading and unloading operations are among the most critical and frequently repeated activities in well testing operations. The analysis of past incidents under similar conditions reveals that incidents related to loading and the falling of suspended loads, which occur with high frequency and intensity, are the most common. In contrast, the incidence rate of toxic and flammable gas leaks is significantly lower compared to the rate of accidents caused by loading operations. The absence of limitations and the potential for defining effective protective layers for controlling toxic and flammable gas leaks contribute to the reduction of incidents in this area. In contrast, the number of protective and preventive layers for cargo operations is limited, leading to a higher rate of failure in these layers. Although the severity of consequences from loading operations is generally less than that from explosions and fires, the high frequency of these operations and the increased probability of incidents result in a higher number of accidents and a greater risk level for loading operations compared to other activities.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	N.F.	M.E. Ö
C	80	20
D	60	40
S	40	60
DCP	100	0
DAI	70	30
L	90	10
W	70	30
CR	40	60
SR	70	30
PM	60	40
FA	100	0

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. The experimental procedures were approved by the Non-Interventional Research Ethics Committee of Uskudar University, (approval date: 29 July, 2024, protocol code: 61351342/020-243).

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Research Article
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THE NOTES ON SLANT HELICES ACCORDING TO EQUIFORM FRAME ON SYMPLECTIC SPACE

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Abstract: In this paper, first of all, we define basic definitions, some characterizations and theorems of symplectic space we calculated equiform frame in 4-dimensional symplectic space. Then, we obtain Frenet vectors and curvatures of a symplectic curve due to equiform frame. We have dealed with the properties of k-type slant helix according to equiform frame. It is seen that there exist k-type slant helices for all cases. In addition, we express some characterizations for k-type slant helix according to equiform frame geometry in symplectic regular curves. Finally, we give an example about symplectic space on graphics with symplectic frame on 4-dimensional symplectic space.

Keywords: Frenet vectors, Slant helix, Equiform frame

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1. Introduction

In recent years, by the coming theory of the curves, researches extend some special curves. Some of them are helices, slant helices, Bertrand curves, associated curves, adjoint curve etc. There are many studies on these special curves. Especially a general helices and slant helices are used for many applications. A general helices is defined that its tangent vector fields makes a constant angle with a fixed direction called the axis of general helices. The notion of slant helices defined by Izumiya and Takeuchi (2004) based on the property that the principal normal lines of the curve make a constant angle with a fixed direction. Moreover, Kula and Yaylı (2005) obtained slant helices and their spherical indicatries. Later, slant helices subject are also presented in 3-,4-, and n- dimensional space, respectively in Ali and Turgut, (2010), Ali et al. (2012), Çiçek Çetin and Bektaş (2020a and 2020b) and Yılmaz and Bektaş (2020) different dimensions. Afterwards, another property of helices are discussed in Kula and Yaylı (2005), Ali and Lopez, (2011) and Önder et al. (2008). Ferrandez et al. (2002) also researchers studied k-type slant helices in E_1^4. In particular, authors defined (k,m)-type slant helices in E^4, and discussed them for partially and pseudo null curves in E_1^4 in Yılmaz and Bektaş, (2018 and 2020). Çetin and Bektaş (2019) introduced some characteizations of symplectic space. Also, Bulut (2021a, 2021b and 2023), Bulut and Eker (2023), Bulut and Tartık (2021) and Bulut and Bektaş, (2020) authors deal with k -and (k,m)-type slant helices in different spacetime. Furthermore, there are many studies about symplectic curves in 4-dimensional symplectic space and equiform differential geometry (Struik, 1988; Abdel Aziz, 2015).

The word symplectic was first used by Weyl in the sense of complex to describe symplectic groups. Some scientist accepts symplectic geometry as the language of classical mechanics. In fact, the basis of Hamilton and Kahler manifolds, which play an important role in mathematics and theoretical physics, is based on symplectic geometry. The origin of Hamilton mechanics is symplectic geometry, and the base-spaces of classical systems play an important role in the structure of symplectic manifold. Symplectic geometry is at basis of optics. On the other hand, symplectic geometry also has important connections with dynamic systems, integrable systems, algebraic geometry and global analysis. Symplectic geometry is studied by geometers (Chern and Wang, 1947; Kamran and Olver, 2009). Symplectic spaces were first studied by Chern and Wang (1947) as local symplectic invariants of Euclidean subspaces. Symplectic space differs from Euclidean space in terms of metric and arc length. Kamran and Olver (2009) obtained the Frenet frame of curves using local symplectic invariants. Authors, introduced the concept of symplectic arc length for curves. And they constructed an adapted symplectic Frenet frame and expressed 2n - 1 local differential invariants that they called symplectic curvatures of the curve

According to our opinion, slant helices should be researched equiform frame in symplectic space. Because we know that symplectic curves play an important role in modern geometry. Also symlectic space are studied by some geometers. They proved that up to a rigid symplectic motion of R^{2n}, there exists a unique curve

with symplectic curvatures.
In this paper, we focus on k-type and (k,m)- type slant helix according to equiform frame and we also consider some characterizations for (k,m)- type slant helix of symplectic regular curves.

2. Materials and Methods

Let us introduced some definition for symplectic space.
For, any vectors,$u = (x^1, x^2, \dots, x^n, y^1, \dots, y^n), v = (\xi^1, \dots, \xi^n, \eta^1, \dots, \eta^n) \in R^{2n}$
Symplectic inner product is given by

$$< u, v >= \varphi(u, v) = \sum_{i=1}^{n} (x_i \eta_i \wedge y_i \xi_i)$$

4-dimensional symplectic space $Sim = (R^4, \varphi)$ is the vector space R^4 equipped with the standard symplectic form, written as

$$\varphi = \sum dx_i \wedge dy_i$$

(Kamran and Olver, 2009).
Let V be a vector space on the field of real numbers R. If, for each u, v

$$\varphi(u, v) = -\varphi(v, u)$$

It is called anti symmetric bilinear transformation.
Symplectic space with symplectic inner product can be written as

$$< u, v > = \varphi(u, v) = \sum_{i=1}^{2} (x_i \eta_i - y_i \xi_i)$$
$$= x_1 \eta_1 + x_2 \eta_2 - y_1 \xi_1 - y_2 \xi_2$$

here $u = \{x_1, x_2, y_1, y_2\}$ and $v = \{\xi_1, \xi_2, \eta_1, \eta_2\}$
Additionally, the tangent vectors $\{a_1, a_2, a_3, a_4\}$ satisfying the equations

$$\langle a_k, a_l \rangle = \langle a_{2+k}, a_{2+l} \rangle = 0 \;\; 1 \le k, l \le 2,$$
$$\langle a_k, a_{2+l} \rangle = 0 \;\; 1 \le k \ne l \le 2,$$
$$\langle a_k, a_{2+l} \rangle = 1 \;\; 1 \le k \le 2$$

for symplectic frame, structure equations are defined by

$$1 \le i, j \le n$$
$$da_i = \sum_{k=1}^{n} w_{ik} a_k + \sum_{k=1}^{n} \varphi_{ik}\, a_{k+n}$$
$$da_{i+n} = \sum_{k=1}^{n} \theta_{ik} a_k + \sum_{k=1}^{n} w_{ik}\, a_{k+n}$$

here, $\varphi_{ij} = \varphi_{ji}, \theta_{ij} = \theta_{ji}$ (Kamran and Olver, 2009).
Let $z(t) : R \to R^4$ be a symplectic regular curve parametrized by symplectic arc length with symplectic frame. Throughout this paper, we make some notations and calculations for later use. We show that z to indicate differentiation with respect to the parameter t:

$$\dot{z} = \frac{dz}{dt}$$

Definition 2.1. Let $z(t)$ be a symplectic regular curve in $Sim = (R^4, \varphi)$. Then the following non-degeneracy condition is satisfied

$$\langle \dot{z}, \ddot{z} \rangle \ne 0$$

for all $t \in R$.
Definiton 2.2. Let $z(t)$ be a symplectic regular curve, with symplectic arc length s. Then z(s) can be written as

$$s(t) = \int_{t_0}^{t} \langle \dot{z}, \ddot{z} \rangle^{1/3}\, dt$$

for all $t \ge t_0$.
If

$$\int_{t_1}^{t_2} \langle \dot{z}, \ddot{z} \rangle^{1/3}\, dt = t_2 - t_1 \;\; (t_1, t_2 \in I)\; t_1 \le t_2$$

symplectic regular curve is said to parametrized by symplectic arc length. The symplectic arc length parameter corresponds to the equaffine arc length for plane curves.
Taking the extrerior differential of above equation, the symplectic arc length element is obtained by

$$ds = \langle \dot{z}, \ddot{z} \rangle^{1/3} dt$$

and the arc length derivative operator is

$$D = \frac{d}{ds} = \langle \dot{z}, \ddot{z} \rangle^{-1/3} \frac{d}{dt}$$

In our notion, the symplectic arc length derivative operator is defined by

$$z' = \frac{dz}{ds}$$

Definiton 2.3. A symplectic regular curve is parametrized by symplectic arc length if it satisfies

$$\langle \dot{z}, \ddot{z} \rangle = 1$$

for all $t \in R$.
Let $z(s)$ be a symplectic regular curve parametrized by arc length with $\{a_1, a_2, a_3, a_4\}$ a symplectic frame. Then, Frenet equations can be written (equation 1)

$$\begin{aligned} a_1{}'(s) &= a_3(s) \\ a_2'(s) &= H_2(s) a_4(s) \\ a_3'(s) &= k_1(s) a_1(s) \\ a_4'(s) &= a_1(s) + k_2(s) a_2(s) \end{aligned} \tag{1}$$

where $H_2(s) = cost(\ne 0)$ (Valiquette, 2012).

3. k–Type Slant Helices According to Symplectic Equiform Frame

Definiton 3.1. Let $z: I \to R^4$ be a symplectic regular curve according to equiform frame $\{V_1, V_2, V_3, V_4\}$. We say that if there exists a (non-zero) constant vector field $U \in R^4$ such that

$$\langle V_{k+1}, U \rangle = c = const, \;\; 0 \le k \le 3$$

z is a k- type slant helix.
Theorem 3.2. Let $z: I \to R^4$ be a symplectic regular curve according to symplectic equiform frame $\{V_1, V_2, V_3, V_4\}$. Then z is $0-$type slant helix iff (equation 2)

$$\langle V_2, U\rangle = \frac{cK_1{}^2 - c\rho^2}{\rho^2} \quad (2)$$

Proof . Suppose that z is a 0 −type slant helix and let U be the constant vector field, we get (equation 3)

$$\langle V_1, U\rangle = c. \quad (3)$$

where c is constant.
differentiating the relation (2) and using Frenet equation (1), we find,

$$K_1\langle V_1, U\rangle + \rho\langle V_3, U\rangle = 0$$

Or

$$K_1 c + \rho\langle V_3, U\rangle = 0$$

and

$$\langle V_3, U\rangle = -\frac{cK_1}{\rho}$$

Differentiating above equation and using Frenet equation (2), we hence find,

$$K_1\langle V_3, U\rangle + \langle V_1, U\rangle + \rho\langle V_2, U\rangle = \frac{cK_1'\rho + cK_1\rho'}{\rho^2}$$

So, we obtain,

$$\langle V_2, U\rangle = \frac{cK_1{}^2 - c\rho^2}{\rho^2}$$

Hence the theorem is proven.
Theorem 3.3. Let $z: I \to R^4$ be a symplectic regular curve according to equiform frame $\{V_1, V_2, V_3, V_4\}$. Then z is 1−type slant helix iff

$$\langle V_1, U\rangle = \frac{-cK_1'K_2 + cK_1K_2' + cK_1 - cK_3K_2{}^2}{K_2{}^2}$$

Proof. Suppose that z is a 1 −type slant helix and let U be the constant vector field, we have equation 4:

$$\langle V_2, U\rangle = c \quad (4)$$

By taking derivative on both sides of (4), and using Frenet equation (1), we find,

$$K_1\langle V_2, U\rangle + K_2\langle V_4, U\rangle = 0$$

and .

$$\langle V_4, U\rangle = -\frac{K_1\, c}{K_2}$$

Similarly, differentiating above and using Frenet equations (1), we find,

$$\rho\langle V_1, U\rangle + K_3\langle V_2, U\rangle + K_1\langle V_4, U\rangle = \frac{-cK_1{}'K_2 + cK_1K_2{}'}{K_2{}^2}$$

or

$$\langle V_1, U\rangle = \frac{-cK_1'\,K_2 + cK_1K_2' + cK_1 - cK_3K_2{}^2}{K_2{}^2}$$

The theorem is proven.
Theorem 3.4. Let $z: I \to R^4$ be a symplectic regular curve respect to symplectic equiform frame $\{V_1, V_2, V_3, V_4\}$. Then z(s) is 2 −type slant helix iff

$$\langle V_4, U\rangle = -\frac{cK_1{}^2 - c\rho}{\rho K_2}$$

Proof. Suppose that z(s) is a 2 −type slant helix and let U be the constant vector field, we have equation 5:

$$\langle V_3, U\rangle = c \quad (5)$$

differentiating equation (5) and using Frenet equation (1), we obtain that,

$$K_1\langle V_3, U\rangle + \langle V_1, U\rangle + \rho\langle V_2, U\rangle = 0$$

or

$$\langle V_1, U\rangle + \rho\langle V_2, U\rangle = -cK_1$$
$$\langle V_3, U\rangle = -\frac{K_1\, c_1}{\rho}$$

Similarly, differentiating above equation and using Frenet equation (1), we obtain,

$$K_1\langle V_1, U\rangle + \rho\langle V_3, U\rangle + \rho K_1\langle V_2, U\rangle + \rho K_2\langle V_4, U\rangle = 0$$

or,

$$K_1(\langle V_1, U\rangle + \rho\langle V_2, U\rangle) = -cK_1{}^2$$

Thus, we can easily seen that,

$$\langle V_4, U\rangle = -\frac{cK_1{}^2 - c\rho}{\rho K_2}$$

So, the theorem is proven.
Theorem 3.1.5. Let $z: I \to R^4$ be a symplectic regular curve according to symplectic equiform frame $\{V_1, V_2, V_3, V_4\}$. Then z is 3 −type slant helix iff

$$\langle V_2, U\rangle = \frac{-cK_1' - cK_3K_2 + cK_1{}^2 - \rho^2\langle V_3, U\rangle}{-cK_1{}^2 - K_3K_1 + \rho K_3{}'}$$
$$\langle V_1, U\rangle = -\frac{K_3c_1 + K_1c_4}{\rho}$$

Proof. Assume that z is a 3 −type slant helix and let U be the constant vector field, we have equation 6:

$$\langle V_4, U\rangle = c \quad (6)$$

Differentiating equation (6) and using Frenet equations (1), we find,

$$\rho\langle V_1, U\rangle + K_3\langle V_2, U\rangle + K_1\langle V_4, U\rangle = 0$$

Similarly, differentiating above equation and using Frenet equations (1), we get,

$$\rho\langle V_1, U\rangle + K_3\langle V_2, U\rangle = -cK_1$$

Differentiating again, we obtain

$$\rho'\,\langle V_1, U\rangle + \rho^2\langle V_3, U\rangle + K_3'\,\langle V_2, U\rangle = -cK_1' - cK_3K_2 + cK_1{}^2$$

Thus, we get,

$$\langle V_2, U\rangle = \frac{-cK_1' - cK_3K_2 + cK_1{}^2 - \rho^2\langle V_3, U\rangle}{-cK_1{}^2 - K_3K_1 + \rho K_3{}'}$$

Thus, the theorem is proven.
Example 3.8. Let's take the following curve

$$z(s) = \frac{1}{\sqrt{5}}\left(shs, \frac{1}{2}s^2 + 2s, chs, \frac{1}{2}s^2 - 2s\right).$$

Figure 1. Then,

$$a_1(s) = z'(s) = \frac{1}{\sqrt{5}}(chs, s+2, shs, s-2)$$

and

$$a_3(s) = z''(s) = \frac{1}{\sqrt{5}}(shs, 1, chs, 1).$$

Thus $z(s)$ is a symplectic regular curve. In addition

$$a_2(s) = \frac{1}{\sqrt{5}}(\frac{4}{5}chs, -\frac{1}{5}(s+2), \frac{4}{5}shs, -\frac{1}{5}(s-2),$$

$$a_4(s) = \frac{5}{4\sqrt{5}}(4shs, -1, 4chs, -1).$$

Since $\rho = 1$, we obtain Frenet vectors respect to equiform frame ,

$$a_1(s) = V_1(s) = \frac{1}{\sqrt{5}}(chs, s+2, shs, s-2)$$

$$a_2(s) = V_2(s) = \frac{1}{\sqrt{5}}(\frac{4}{5}chs, -\frac{1}{5}(s+2), \frac{4}{5}shs, -\frac{1}{5}(s-2)$$

$$a_3(s) = V_3(s) = \frac{1}{\sqrt{5}}(shs, 1, chs, 1)$$

$$a_4(s) = V_3(s) = \frac{5}{4\sqrt{5}}(4shs, -1, 4chs, -1).$$

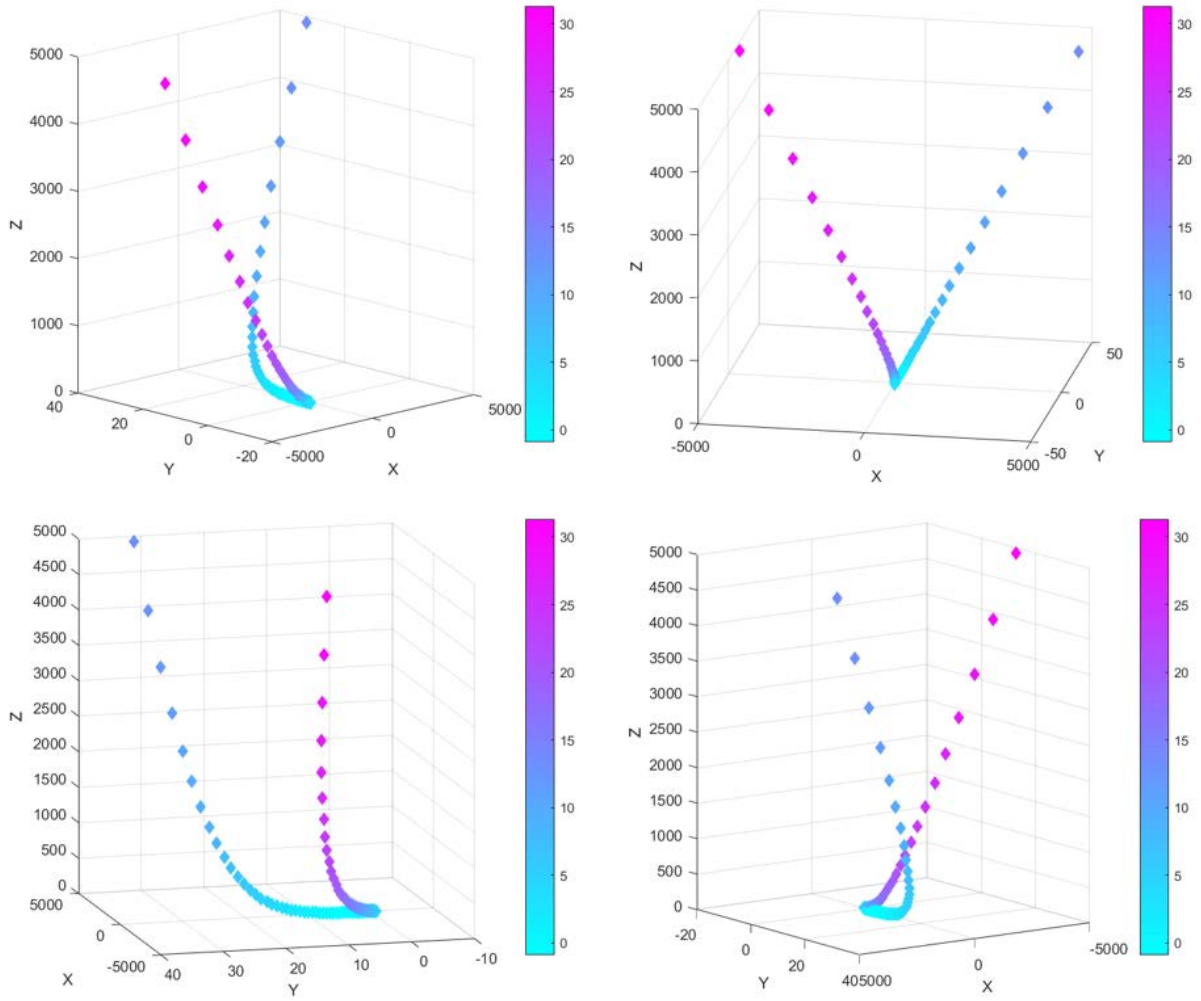

Figure 1. Symplectic regular curve $z(s)$.

This curve in R^4 is plotted with a code that represents the fourth dimension with a color scale.

4. Conclusion

In this study, we especially examined slant helices obtained by symplectic equiform frame. Moreover, we defined basic definition and theorem with symplectic equiform frame. It is seen that there exist k-type slant helices for all cases. Since helices are natural twist structures, examining the symplectic spiral can help to research on connection of contact and symplectic geometries.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	E.Ç.Ç.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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Research Article
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NUMERICAL ANALYSIS OF A TWO-LAYER PCM BASED BATTERY THERMAL MANAGEMENT SYSTEM FOR DIFFERENT MATERIAL PROPERTIES

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Abstract: The design and numerical analysis of the two-layer PCM (Phase Change Material)-based thermal management system for a 18650-type lithium-ion battery have been performed. In relation to simulation, the coefficient of thermal conductivity and melting temperature of the first layer of PCMs are varied. Other parameters are made identical to that of the next layer's parameters in order that the generation of two different layers of PCMs can be attained: PCM-1 and PCM-2. To obtain a more realistic approach in the numerical analysis, the battery thermal model was created in the COMSOL-MATLAB interface using the experimental internal resistance data obtained for 18650 type Li-ion batteries in the literature. While a cheaper and more accessible material with a thermal conductivity of 0.2 W/mK and a melting point of 50 °C was used in the PCM-2 layer, the thermal conductivity was changed as 0.2, 1 and 5 W/mK and the melting point was changed as 30, 40 and 50 °C in the PCM-1 layer. In this way, for PCM layers with different thickness (t_{pcm}), the system was optimized at two different discharge rates, 5C and 7C. As a result of the numerical analysis, it was determined that the optimum t_{pcm}, $k_{pcm,1}$ and T_m values for the 5C discharge rate were 2 mm, 0.2 W/mK and 40 °C, respectively; and the optimum t_{pcm}, $k_{pcm,1}$ and T_m values for the 7C discharge rate were 4 mm, 5 W/mK and 40 °C, respectively.

Keywords: Two-layer, Li-ion battery, Phase change material, Battery thermal management

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1. Introduction

With the knowledge that fossil fuels will run out in the near future, interest in electric vehicles is increasing day by day (Raijmakers et al., 2019). Although electric vehicles provide affordable, clean, and comfortable transportation, their performance and sustainability are largely dependent on the efficiency of the battery systems that power them (Barré et al., 2013). Lithium-ion (Li-ion) battery systems are widely preferred in electric vehicles due to their long cycle life, high power density and low weight (Zou et al., 2018). One of the most important disadvantages of Li-ion battery systems is that their performance and reliability are highly dependent on temperature (Kim et al., 2019). During their operation, high ambient temperatures and high charge/discharge rates can increase the battery temperature excessively. High temperatures can cause irreversible performance and life losses in the battery, and even serious reactions that can result in fire (Safdari et al., 2020). In many studies, safe temperature ranges for Li-ion battery systems have been specified as 50-60 °C (Ling et al., 2015; Kavasoğulları et al., 2023). Battery thermal management systems (BTMS) have been developed to minimize the effects of temperature on the battery and to keep the battery within reliable temperature ranges.

Phase change materials (PCM) are frequently preferred in battery thermal management systems due to their high latent heat (Yang et al., 2023; Moralı 2023). When these materials are applied in the battery pack, both good control of the battery cell temperature and uniform distribution of temperature throughout the battery pack can be achieved (Murali et al., 2021; Kavasoğulları et al., 2024). In PCM-based battery thermal management systems, paraffin and its derivatives are widely used due to their relatively cheap and accessible nature (Maknikar and Pawar, 2023). On the other hand, the low thermal conductivity of these types of materials limits their use, especially under severe operating conditions (Luo et al., 2024). These types of materials act as insulation materials around the battery, especially after phase change, and cause heat to accumulate around the battery, thus causing the battery temperature to increase rapidly (Chen et al., 2024). To prevent this, some researchers have suggested adding certain amounts of nano-particle materials such as graphene, titanium oxide (TiO2), iron oxide (Fe2O3) and alumina (Al2O3) into the PCM material (Talele and Zhao, 2023; Wang et al., 2024; Vyas

et al., 2024). Although PCM thermal conductivity can be significantly improved with this method, the added nanoparticles generally reduce the PCM latent heat (Radomska et al., 2020). In addition, since the addition of such materials to the PCM material requires an additional process and material, the system cost also increases. In order to increase the PCM performance by providing good thermal conductivity and to reduce the system cost, some researchers have proposed multilayer PCMs consisting of different PCMs. In their study, Kang et al. (2024) applied the three-layer PCM system to the battery pack and performed the numerical analysis of the system. As a result of the analysis, they reported that the three-layer PCM system reduced the battery temperature by 13.61 °C and the temperature difference in the battery pack by 2.54 °C compared to the system without PCM. Jilte et al. (2021) worked on two different types of designs for the two-layer PCM system, radial and longitudinal. As a result of the study, they determined that radial PCM layers provide better temperature control. In another study, Kang et al. (2023) performed the experimental and numerical analysis of longitudinal multilayer PCMs using graphene and paraffin. As a result of the study, they determined that the multilayer PCM system reduced the battery temperature by 32.6% at an ambient temperature of 20 °C and a discharge rate of 5C. Shivram and Harish (2024) numerically modeled a two-layer PCM system containing nanoparticles. The researchers used PCM with a melting point of approximately 27 °C in the first layer and a melting point of 82 °C in the second layer. As a result of the study, they revealed that adding nanoparticles shortens the PCM melting time and increases the heat transfer rate.

As can be understood from the literature research, studies on multi-layer PCMs in BTMSs are quite limited. In this study, a two-layer PCM system in the radial direction was designed and its numerical analysis was performed. In the modeled system, the first layer used a PCM with a melting point of 30, 40 and 50 °C; the thermal conductivity coefficient was changed as 0.2; 1 and 5 W/mK, and the second layer used a PCM with a thermal conductivity coefficient and melting point kept constant at 0.2 W/mK and 50 °C, respectively. The PCM thicknesses were also changed to be the same as 2, 3 and 4 mm. In this way, it is aimed to reduce the system cost by using relatively cheaper and available PCM in the second layer. To ensure a realistic representation of the battery, a battery thermal model was created in COMSOL Multiphysics and MATLAB software using the battery properties obtained experimentally in the literature. In this way, BTMS was optimized at two different discharge rates, 5C and 7C.

2. Materials and Methods

The BTMS proposed in the study is shown in Figure 1. The system consists of a Li-ion battery cell and two separate PCM layers. In order to separate the PCM layers from each other and to keep the system together, an aluminum shell with high thermal conductivity is placed between the layers and at the outermost part.

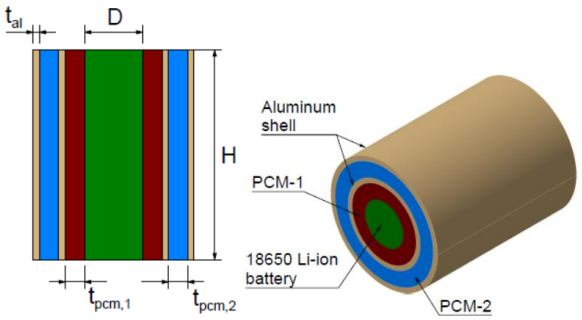

Figure 1. The modeled BTMS in the study.

In the BTMS analyzed, a 2.4 Ah capacity Li-ion battery of type 18650 (D = 18 mm and H = 65 mm) was considered (Lai et al., 2024). The heights of the PCM-1, PCM-2 and aluminum layers used in the system are equal to the battery height (H) and their thicknesses are determined as $t_{pcm,1}$, $t_{pcm,2}$ and t_{al}, respectively. $t_{pcm,1}$ and $t_{pcm,2}$ were changed within the scope of the analysis. t_{al} was taken as 1 mm to reduce thermal resistance. The thermophysical properties of the materials used are summarized in Table 1. As can be understood from the table, except for the melting temperature (T_m) and thermal conductivity (k_s and k_l), all other properties of PCM-1 and PCM-2 are the same. In the calculations, the k_s value of PCM-1 was changed to be 0.2; 1 and 5 W/mK, and the T_m value was changed to be 30, 40 and 50 °C. In PCM-2, the k_s and T_m values were kept constant at 0.2 W/mK and 50 °C, respectively. The thermophysical properties of the Li-ion battery and aluminum were taken from the COMSOL Multiphysics v6.2 software library (COMSOL, 2024).

2.1. Mathematical Modelling

The modeled system, as can be seen in Figure 1, consists of 18650 type cylindrical battery, PCM-1, Aluminum shell, PCM-2 and Aluminum shell layers from inside to outside. Here, a certain amount of current passes through the battery cell according to the given discharge rate and heat is generated due to its internal resistance. The heat released in the battery is absorbed by the PCM layers and the battery temperature is tried to be kept under control. When the heat absorbed by the PCM layers reaches a sufficient level, liquefaction occurs in the PCM. Accordingly, to determine the temperature and phase change behavior of the system, continuity, momentum and energy equations in all layers and phase change equations in PCM-1 and PCM-2 layers must be solved. The following assumptions were made to simplify the solution:

- Heat transfer by radiation is neglected.
- It is assumed that the system is completely insulated from the outside.
- It is assumed that the thermophysical properties of the battery, PCMs and Aluminum materials do not change with temperature.
- The battery cell used can be discharged at the 5C and 7C rates determined in the analysis.

Table 1. The thermophysical properties of the materials used in the study

Property	Definition	Li-ion cell (COMSOL 2024)	Aluminum (COMSOL 2024)	PCM-1 (El Idi et al. 2021)	PCM-2 (El Idi et al. 2021)
ρ_s, kg/m³	Solid phase density	3600	2730	870	870
cp_s, J/kgK	Solid phase specific heat	881	893	2400	2400
k_s, W/mK	Solid phase heat conduction	1	155	0.2, 1 5	0.2
T_m, °C	Melting point	-	-	30, 40, 50	50
LH, kJ/kg	Latent heat	-	-	179	179
ρ_l, kg/m³	Liquid phase density	-	-	760	760
cp_l, J/kgK	Liquid phase specific heat	-	-	1800	1800
k_l, W/mK	Liquid phase heat conduction	-	-	k_s	0.2
μ, Pa.s	Viscosity	-	-	0.00342	0.00342
β, 1/K	Thermal expansion coefficient	-	-	0.0005	0.0005

The conservation and phase change equations for the axisymmetric problem modeled in COMSOL Multiphysics software are given below. The energy equation for the battery side can be written as in equation 1:

$$\rho_b C_{p,b} \frac{\partial T_b}{\partial t} = k_b \nabla^2 T + \frac{Q_{gen}}{V_b} \quad (1)$$

Here ρ_b, $C_{p,b}$, k_b and V_b are the density, specific heat, heat transfer coefficient and volume for the battery, respectively. Q_{gen} is the heat generated in the battery and was described by Bernardi et al. (1985) with the following equation 2:

$$Q_{gen} = Q_{ir} + Q_{rev} \quad (2)$$

In equation 2, Q_{ir} and Q_{rev} are the irreversible and reversible heat amounts produced in the battery, respectively. Since Q_{ir} and Q_{rev} depend on the internal resistance, current and temperature, the total heat produced, Q_{gen}, can also be expressed by the following equation 3:

$$Q_{gen} = I^2 R - IT \frac{\partial U_{ocv}}{\partial T} \quad (3)$$

Here I, R, T and $\partial U_{ocv}/\partial T$ are the current (ampere), internal resistance (ohm), battery temperature (K) and short circuit voltage coefficient (V/K), respectively. In equation 3), the current I is found by multiplying the battery capacity with the discharge rate. In order to make a more realistic approach, the equations depending on temperature and SOC (State of charge) obtained experimentally by Lai et al. (2019) were used when finding the R value. The equations suggested by the researchers are presented below (equations 4a-e):

$$T = 293K: R = 166 - 1.334 \times SOC + 6.559 \times SOC^2 - 16.531 \times SOC^3 + 22.391 \times SOC^4 - 15.496 \times SOC^5 + 4.301 \times SOC^6 \quad (4a)$$

$$T = 303K: R = 107 - 793 \times SOC + 4.036 \times SOC^2 - 10.514 \times SOC^3 + 14.700 \times SOC^4 - 10.480 \times SOC^5 + 2.989 \times SOC^6 \quad (4b)$$

$$T = 313K: R = 66 - 382 \times SOC + 1.962 \times SOC^2 - 5.181 \times SOC^3 + 7.378 \times SOC^4 - 5.365 \times SOC^5 + 1.559 \times SOC^6 \quad (4c)$$

$$T = 323K: R = 58 - 355 \times SOC + 1.898 \times SOC^2 - 5.121 \times SOC^3 + 7.367 \times SOC^4 - 5.374 \times SOC^5 + 1.559 \times SOC^6 \quad (4d)$$

$$T = 333K: R = 48 - 233 \times SOC + 1.225 \times SOC^2 - 3.263 \times SOC^3 + 4.667 \times SOC^4 - 3.406 \times SOC^5 + 992 \times SOC^6 \quad (4e)$$

As can be seen above, the given equations were obtained for five different temperature values, 293, 303, 313, 323 and 333 K. For intermediate temperature values, interpolation was performed with the help of a MATLAB software code and the obtained internal resistance values were transferred to COMSOL software simultaneously. For temperature values greater than 333 K, the internal resistance value was calculated using equation 4e) as suggested by Lai et al. (2019). The short circuit voltage coefficient, $\partial U_{ocv}/\partial T$, was also calculated with the equation obtained experimentally in the same literature study (equation 5):

$$\frac{\partial U_{ocv}}{\partial T} = -0{,}355 + 2{,}154 \times SOC - 2{,}869 \times SOC^2 + 1{,}028 \times SOC^3 \quad (5)$$

The Q_{gen} value defined by equation 3 was calculated by

running equations 5, 4a, 4b, 4c, 4d and 4e simultaneously in COMSOL-MATLAB. The working method of the COMSOL-MATLAB couple is presented in Figure 2. As can be seen in the figure, in the first step, the T and SOC information was sent from the COMSOL software to the MATLAB code and then the R value was calculated in the MATLAB code and transferred to the COMSOL software. In the COMSOL software, the Q_{gen} value was determined using equations 5 and 3.

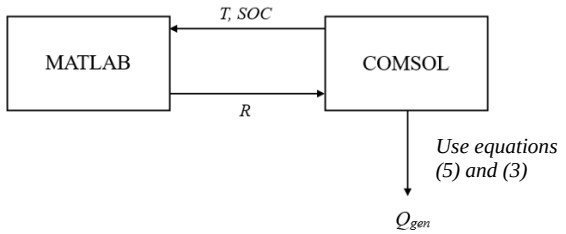

Figure 2. The calculation procedure of Q_{gen}.

For the axisymmetric system, continuity and momentum equations 6 and 7in PCM layers can be written as follows (Samimi et al., 2016):

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r)+\frac{\partial}{\partial z}(\rho v_z)=0 \tag{6}$$

$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=-\nabla P+\rho\vec{g}+\nabla\bar{\tau}+\vec{F} \tag{7}$$

In the above equations, v and u are velocity components (m/s), g and τ are gravitational acceleration (9.81 m/s^2) and shear stress (N/m^2), respectively. In equation 7), F is the total volume force (N/m^3) in the r and z directions and its value in the r direction will be F_r = 0. The component in the z-direction can be calculated with the following equation 8:

$$F_z=\rho g\beta(T-T_{ref}) \tag{8}$$

Here, T_{ref} is the reference temperature and is taken as 293.15 K. The energy equation for PCM is given in equation 9):

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p u\cdot\nabla T=\nabla\cdot(k\nabla T) \tag{9}$$

The effective thermophysical properties for PCM layers can be found with the following equations 10a-d:

$$k_{pcm}=\theta_1 k_s+\theta_2 k_l \tag{10a}$$

$$\rho_{pcm}=\theta_1\rho_s+\theta_2\rho_l \tag{10b}$$

$$C_{p,pcm}=\frac{1}{\rho_{pcm}}\left(\theta_1\rho_s C_{p,s}+\theta_2\rho_l C_{p,l}\right)+LH\frac{\partial\alpha_{pcm}}{\partial T} \tag{10c}$$

$$\alpha_{pcm}=\frac{1}{2}\frac{\theta_2\rho_l-\theta_1\rho_s}{\theta_1\rho_s+\theta_2\rho_l} \tag{10d}$$

Here, the subscripts s and l represent the properties in the solid and liquid phases, respectively, and are given in Table 1. α_{pcm} given in equation 10c is the PCM thermal diffusion coefficient (m/s^2). θ_1 and θ_2 indicate the ratio of solid and liquid materials in the PCM at any moment, respectively, and the sum of the two will be equal to one. Since heat transfer on the aluminum side will only occur by conduction, the energy equation 11 can be written as follows:

$$\rho C_p\frac{\partial T}{\partial t}-k\nabla T=0 \tag{11}$$

2.2. Initial and Boundary Conditions

In order to solve the equations given above numerically, the initial and boundary conditions must be defined. Since the system is assumed to be completely isolated, the isolation boundary condition for all boundaries can be written as follows (equation 12):

$$-n\cdot q=0 \tag{12}$$

In equation 12, n represents any coordinate. It is assumed that the temperature of the entire system is the same at t = 0. The relevant initial condition can be written as follows (equation 13):

$$\begin{aligned} t=0;\ T_b(r,\Phi,z)&=T_{pcm,1}(r,\Phi,z)\\ &=T_{al,1}(r,\Phi,z)\\ &=T_{pcm,2}(r,\Phi,z)\\ &=T_{al,2}(r,\Phi,z)=T_0 \end{aligned} \tag{13}$$

Here, the initial temperature T_0 is taken as 20 °C. The conduction boundary conditions for the Battery-PCM-1, PCM-1-Aluminum, Aluminum-PCM-2 and PCM-2-Aluminum interfaces are given in equations 14, 15, 16 and 17, respectively.

$$k_b\frac{\partial T}{\partial n}=k_{pcm,1}\frac{\partial T}{\partial n} \tag{14}$$

$$k_{pcm,1}\frac{\partial T}{\partial n}=k_{al}\frac{\partial T}{\partial n} \tag{15}$$

$$k_{al}\frac{\partial T}{\partial n}=k_{pcm,2}\frac{\partial T}{\partial n} \tag{16}$$

$$k_{pcm,2}\frac{\partial T}{\partial n}=k_{al}\frac{\partial T}{\partial n} \tag{17}$$

2.3. Solution Procedure and Validation

In the numerical analysis performed in the study, COMSOL Multiphysics software was used to solve the conservation and phase change equations. Battery side thermal modeling in the system was performed with the COMSOL-MATLAB interface, considering the change of internal resistance with temperature. PCM temperature and phase change characteristics were determined using the "Heat Transfer in Solids and Fluids" module in the software. The momentum equations of PCM in the liquid phase were solved using the "Laminar Flow" module.

As stated in the previous section, the battery thermal model was created using the equations obtained in the literature study conducted by Lai et al. (2019). Before the analyzes performed within the scope of the study, the model created in the COMSOL-MATLAB interface

was verified with the same literature study. The results obtained in the verification analysis are shown in Figure 3. As shown, the COMSOL-MATLAB thermal model is highly consistent with the literature, with the maximum discrepancy determined to be 2%.

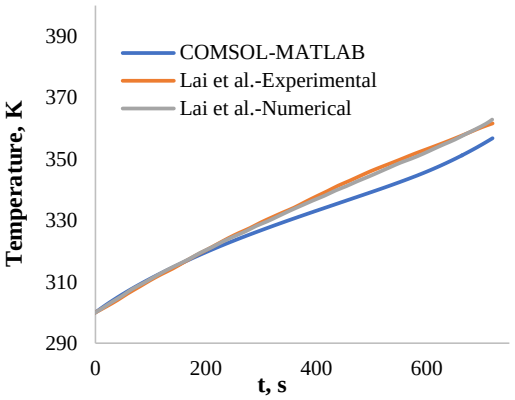

Figure 3. The validation of the COMSOL-MATLAB model created in the study with literature.

As is known, the mesh structure created in numerical studies also greatly affects the results. The mesh structure used in the numerical analysis performed in the study is shown in Figure 4. The mesh structure was prepared by dividing the calculation area into squares of a certain length. Since the mesh element dimensions are constant throughout the geometry, a mesh structure with an average element quality of 1.0 was obtained. The graph in Figure 5 shows the battery center temperatures obtained at 7C discharge rate with different mesh element dimensions. As can be seen in the graph, the temperatures obtained at the specified mesh element dimensions have almost never changed. Reducing the mesh element size will increase the total number of elements and therefore increase the calculation time. For this reason, the largest sized mesh element (2.5 mm) was preferred in the analyses performed to save time and energy.

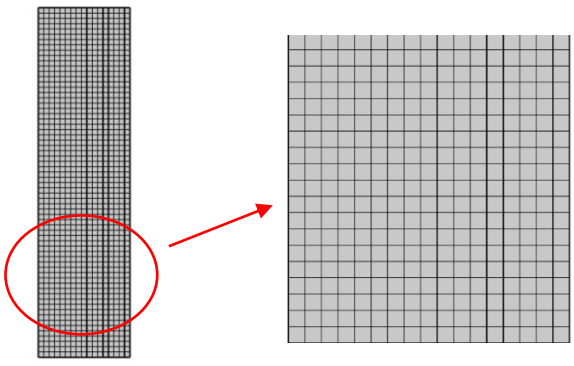

Figure 4. The mesh structure used in the numerical analysis.

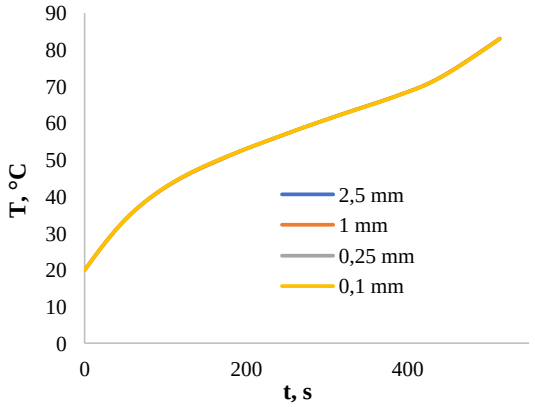

Figure 5. The temperature values obtained for different mesh element sizes.

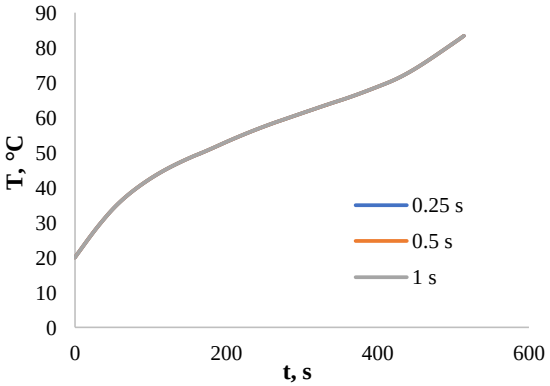

Figure 6. The results of time step size independence analysis.

Since the continuity, momentum and energy equations given in the study are time dependent, an analysis of independence from the time step size was also performed. In the analysis performed, numerical calculations were made for three different time step sizes, 0.25, 0.5 and 1 second. The battery core temperatures obtained at a discharge rate of 7C as a result of the calculation are shown in the graph in Figure 6. As can be seen in the figure, almost the same results were obtained for all determined time step sizes. Therefore, the time step size was taken as 1 second for an economical calculation.

3. Results and Discussion

In the presented study, as mentioned before, a two-layer PCM system with different properties was modeled. While the PCM with changing material properties was used in the first PCM layer (PCM-1), the material properties of the PCM in the second layer (PCM-2) were kept constant. Accordingly, the thermal conductivity of PCM-1 was changed as 0.2, 1 and 5 W/mK; and the melting point was changed as 30, 40 and 50 °C, while the other properties of PCM-1 were the same with PCM-2. The thermal conductivity of PCM-2 was taken as 0.2 W/mK and the melting temperature as 50 °C. In order to see the effect of the

PCM material thickness on the system performance, the t_{pcm} was changed as 2, 3 and 4 mm, which would be the same in both layers. In the created numerical model, the multilayer PCM system was subjected to discharge at two different speeds, 5C and 7C, and the discharge times for the determined discharge rates were calculated as 720 and 514 seconds, respectively. The value reached by the battery center point temperature (T_b) at the end of the calculated discharge times was taken as the performance indicator in the system.

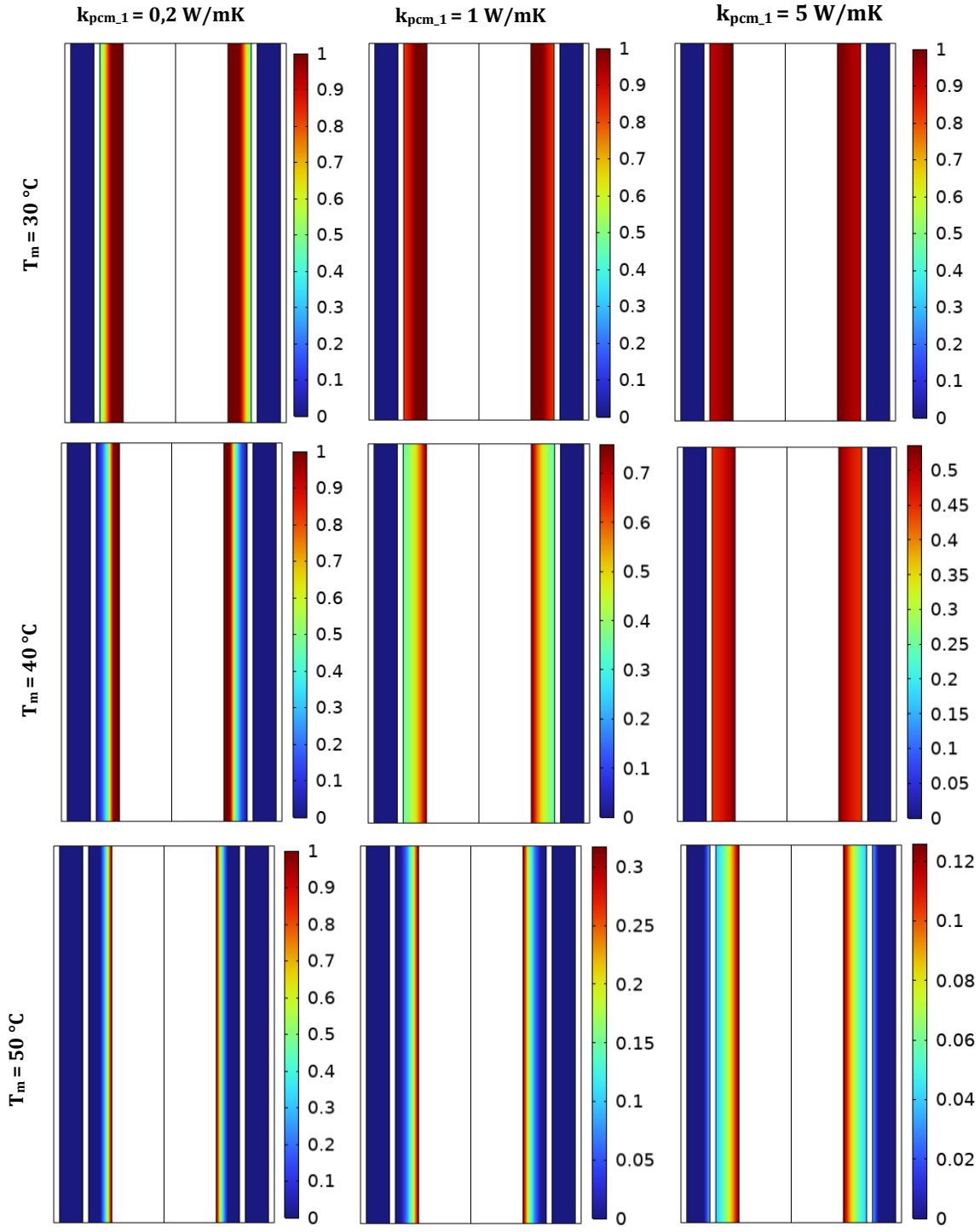

Figure 7. The liquefaction contours obtained for different $k_{pcm,1}$ and T_m values at 5C discharge rate (t_{pcm} = 4 mm).

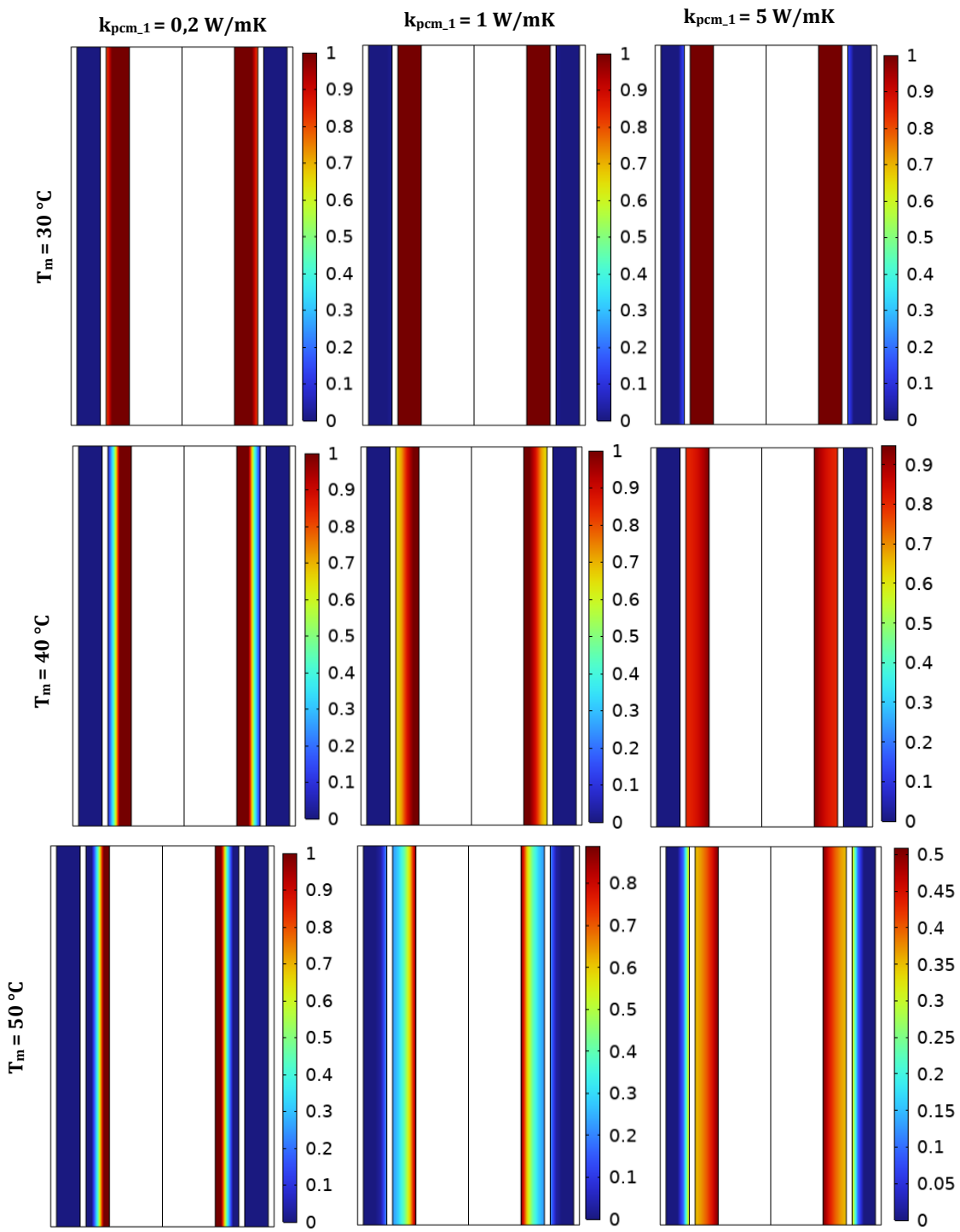

Figure 8. The liquefaction contours obtained for different $k_{pcm,1}$ and T_m values at 7C discharge rate (t_{pcm} = 4 mm).

The liquefaction contours obtained for different $k_{pcm,1}$ and T_m values for different 4 mm t_{pcm} at the end of the discharge time at 5C speed are shown in Figure 7. When different T_m values are examined, it is seen that almost no PCM-2 liquefied at $k_{pcm,1}$. In the system where only 5 W/mK PCM-1 was used, very little liquefaction occurred in PCM-2 at 50 °C. The reason for this is that the amount of heat generated in the battery at 5C discharge rate is relatively low. When different $k_{pcm,1}$ values are examined, it is determined that as the $k_{pcm,1}$ value increases, the amount of liquefactions in inner and outer layers of PCM-1 are closer to each other due to the improvement of heat conduction, that is, the PCM-1 layer liquefied more homogeneously.

Figure 8 shows the liquefaction contours obtained at the end of the discharge period for different $k_{pcm,1}$ and T_m values for 7C discharge rate and 4 mm t_{pcm}. As can be understood from the figure, in the system using PCM-1 with 0.2 W/mK, PCM-2 almost did not melt at all T_m values. The reason for this is that at low $k_{pcm,1}$ values, heat could not be transmitted in PCM-1 and accumulates in the region close to the battery. While almost all of PCM-1 melted at all $k_{pcm,1}$ values for low T_m, increasing T_m value decreased the liquid ratio of PCM-1 and increased the

liquid ratio of PCM-2 at high $k_{pcm,1}$ values. At high $k_{pcm,1}$ values, heat could be transmitted more to PCM-2 layer and PCM-2 layer could be utilized more.

The battery temperature values obtained for T_m values at different thicknesses at 5C discharge rate are given in Figure 9. As can be understood from the graphs, especially at 0.2 W/mK $k_{pcm,1}$ value, increasing the thickness negatively affected the cooling performance of the system and caused the temperature to exceed 60 °C. Increasing the $k_{pcm,1}$ value at the same thickness improved the system performance. Considering the performance and cost parameters of the system, it was determined that using 0.2 W/mK PCM-1 with 2 mm thickness and 40 °C melting point is the most suitable solution.

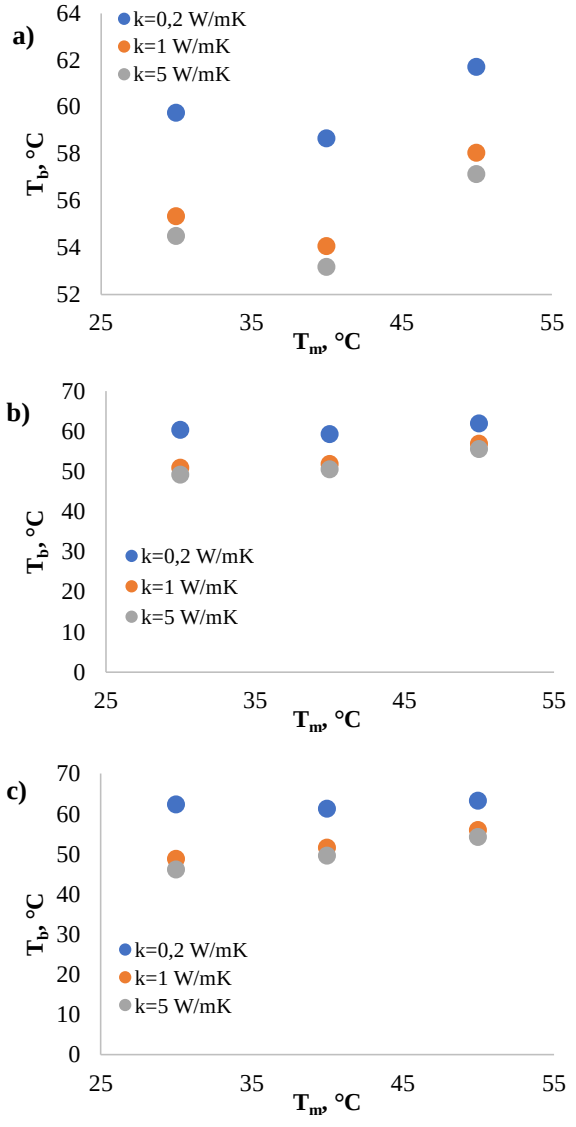

Figure 9. The battery temperature values obtained for different t_{pcm} and T_m values at 5C discharge rate: a) 2 mm, b) 3 mm and c) 4 mm.

Figure 10 shows the change of T_b values with T_m at 7C discharge rate for different $k_{pcm,1}$ values at 2, 3 and 4 mm thicknesses. As can be understood from the figures, as the $k_{pcm,1}$ value increased, T_b values decreased due to better heat transfer to the PCM-2 layer. Increasing the thickness at low $k_{pcm,1}$ values caused T_b values to increase slightly. This can be caused by the greater accumulation of heat in the PCM-1 layer. When the T_m values are considered, at a $k_{pcm,1}$ value of 0.2 W/mK, the T_b value tended to decrease slightly as the T_m value increased. At higher $k_{pcm,1}$ values, T_b first decreased and then increased with the increase in the T_m value. Considering the obtained data, it was determined that the most suitable T_m value was 40 °C. Under the specified conditions, T_b was calculated below 60 °C for only 4 mm thickness, $k_{pcm,1}$ = 5 W/mK and T_m = 40 °C. It was understood that PCM-1 and PCM-2 with a thickness of at least 4 mm should be used at the specified $k_{pcm,1}$ and T_m values for a safe discharge process.

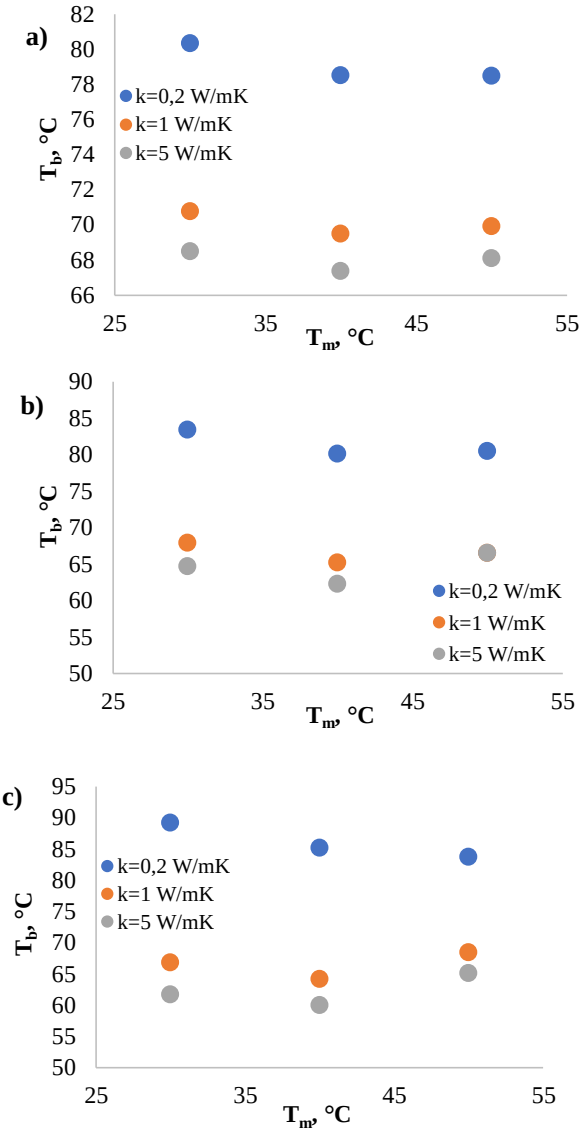

Figure 10. The battery temperature values obtained for different t_{pcm} and T_m values at 7C discharge rate: a) 2 mm, b) 3 mm and c) 4 mm.

4. Conclusion

In the presented study, numerical analysis of a BTMS using two-layer PCM was performed using COMSOL Multiphysics software. The thermal model of the 18650 type Li-ion battery in the system was created in the COMSOL-MATLAB interface using experimental data obtained in the literature. In the numerical analysis, two different PCM layers, namely PCM-1 and PCM-2, were obtained by changing the thermal conductivity ($k_{pcm,1}$) and melting point (T_m) of the PCM in the first layer. The system designed in this way was analyzed for two different discharge rates, 5C and 7C, different PCM layer thicknesses (2, 3 and 4 mm), different $k_{pcm,1}$ (0.2; 1 and 5 W/mK) and different T_m (30, 40 and 50 °C) values. The results obtained as a result of the analysis are summarized below:

• The liquefaction contours obtained for 4 mm t_{pcm} at 5C and 7C discharge rates showed that increasing the $k_{pcm,1}$ value provided more homogeneous liquefaction.

• For 4 mm t_{pcm} at 5C discharge rate, PCM-2 layer was almost not liquefied in all cases.

• When PCM-1 was used with 2 mm thickness, 0.2 W/mK and T_m = 40 °C in the system at 5C discharge rate, the battery temperature could be kept below 60 °C.

• At 7C discharge rate, the battery temperature could be reduced below 60 °C only when it was 4 mm thick, 5 W/mK and T_m = 40 °C. It was understood that PCM thickness should be at least 4 mm for a safe discharge at the determined rate.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	B.K.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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Research Article
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DECOLORIZATION OF ACID YELLOW 17 BY OZONATION AND PEROXONE (O_3/H_2O_2) PROCESS

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Abstract: In this study, the decolorization of Acid Yellow 17, a mono azo dye with a wide range of applications such as in food, textiles, personal care products, and household cleaning products, was investigated in aqueous solutions using ozonation and peroxone processes. The effects of ozone gas flow rate (150, 200, and 250 L/h), ozone gas concentration (5.5, 11, and 16.5 g/m^3), initial dye concentration (100, 200, and 300 mg/L), and hydrogen peroxide concentration (25, 50 and 62.5 mg/L) on decolorization in the batch bubble reactor were investigated. When the ozone gas flow rate was increased from 150 L/h to 200 L/h in the ozonation process, the removal efficiency increased from 70% to 80.2%. At gas flow rates above 200 L/h, removal was negatively affected. The removal efficiency increased with increasing ozone gas concentration, and at the end of the 45-minute reaction time, a removal efficiency of 98% was achieved at an ozone gas concentration of 16 g/m^3. The increase in initial dye concentrations decreases the removal efficiency due to the increase in the amount of pollutant per unit ozone molecule. In the peroxane process, the effect of hydrogen peroxide on color removal was limited. It was determined that the ozonation process was more effective for the removal of Acid Yellow 17 from aqueous solutions.

Keywords: Acid yellow 17, Ozonation, Decolorization, Peroxane

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1. Introduction

Nowadays, when environmental problems threaten humanity, wastewater treatment is essential in terms of water pollution, protection, and sustainability of water resources. The need for innovative treatment processes is increasing due to the inadequacy of conventional wastewater treatment methods. Research in this area is essential to eliminate pollution and ensure economic, flexible, and sustainable processes. With the increase in the amount and types of pollutants in wastewater, especially with the increase in discharge standards, there is a need for research and development of treatment processes. Among the treatment methods investigated, advanced oxidation processes are interesting in the removal of resistant pollutants (Gągol et al., 2018; Değermenci et al., 2019; Gautam et al., 2019; Iqbal et al., 2023). Advanced oxidation processes are oxidation processes that convert organic compounds in wastewater into water and carbon dioxide through the production of free radicals such as hydroxyl radicals ($^{\bullet}OH$), hydroperoxyl radicals ($HO_2^{\bullet}$), sulfate radicals ($SO^{\bullet}_4^-$) and superoxide anion radicals ($O^{\bullet}_2^-$) by various methods (chemical, electrochemical, radiation-induced and cavitation) (Loures et al., 2013; Boczkaj and Fernandes, 2017; Değermenci, 2021; Çobanoğlu and Değermenci, 2022; Priyadarshini et al., 2022; Iqbal et al., 2023).

Ozone is an oxidizing gas consisting of three oxygen atoms. It is unstable, has a short half-life, and is unstorable. Therefore, it is used where it is produced. It is usually generated from dry or pure oxygen using commercial generators by passing it between electrodes with a high potential difference. In ozonation processes, organic and inorganic compounds are oxidized: i. directly by ozone molecules (dominant mechanism in acidic conditions), ii. indirectly by hydroxyl radicals (dominant mechanism in alkaline conditions) (Loures et al., 2013; Boczkaj and Fernandes, 2017; Chen and Wang, 2021; Iqbal et al., 2023). Ozonation has been widely investigated in drinking water and wastewater treatment processes. As pretreatment, the ozonation process enhances biodegradation and can be used to reduce toxic components for biological treatment. As post-treatment, ozonation can improve water quality by removing pollution before discharge. Ozone can be used as O_3/US, O_3/UV, O_3/Catalyst, O_3/H_2O_2, O_3/Cavitation, or combinations thereof (O_3/H_2O_2/US, O_3/H_2O_2/UV, O_3/Catalyst/UV, etc.) to increase hydroxyl radical concentration (Loures et al., 2013; Gągol et al., 2018; Chen and Wang, 2021). O_3/H_2O_2 (peroxane) is one of the advanced oxidation processes based on the development of the ozonation process. H_2O_2 is a strong oxidant that can decompose to HO_2^- and the addition of hydrogen peroxide to the ozonation process leads to ozone decomposition and the formation of the hydroxyl radical.

There are studies investigating the treatment of dye and textile wastewater with ozone and peroxane processes in the literature (Sun et al., 2020; Pham et al., 2022; Shikha Agrawal et al., 2023).

Wastewater containing dyestuffs has reached enormous amounts today, and it is essential to treat them effectively to protect water resources. Acid Yellow 17 (AY 17) is a mono azo dye with a wide range of applications. AY 17 has many uses in textiles, paper, leather, detergents, soaps, cosmetics, and personal care products and is very soluble in water. It damages humans and other living organisms' nervous, respiratory, and cardiovascular systems. Like most dyestuffs, it has carcinogenic, mutagenic, and toxic effects. It has the potential to form toxic intermediates when appropriate treatment alternatives are not used (Alemu and Kerie, 2022; Kannaujiya et al., 2023; Muhammad et al., 2024). Generally, the visible color of dyes in the aquatic environment is not aesthetically appropriate. They also disrupt gas transfer and inhibit photosynthesis by reducing light transmission (Khan et al., 2018; Teli and Nadathur, 2018).

When the literature is examined, it is observed that various treatment methods have been studied for AY 17 removal. In a study using non-living aerobic granular sludge as biosorbent for AY 17 removal, the effects of pH, biosorbent dosage, initial AY 17 concentration, NaCl concentration, and temperature were investigated. It has been reported that the biosorption process is highly dependent on pH, and the optimum pH value is 2. It was stated that the biosorption capacity increased with increasing dye concentration and decreased with biosorption dosage and salt concentration. It was noted that the biosorption process obeyed the Temkin isotherm and pseudo-second-order kinetics. It was stated that non-living aerobic granular sludge could be a low-cost and alternative biosorbent for removing AY 17 (Gao et al., 2010). In a study where activated carbon/α-Fe_2O_3 nanocomposite was used for the adsorption of AY 17 dye, it was reported that the removal was in good agreement with Langmuir. It was also reported that the adsorption data were quite good with Freundlich and Temkin isotherms at higher concentrations of the dye (40–100 mg/L). The removal of AY 17 was shown to fit the pseudo-second-order kinetic model. AC/α-Fe_2O_3 nanocomposite material was reported to be an excellent magnetic adsorbent for removing acid dyes (Ranjithkumar et al., 2014).

Various advanced oxidation processes for AY 17 removal have been investigated in the literature. In a study examining the removal of AY 17 by the Fenton process; pH, temperature, Fe^{2+} concentration, H_2O_2 concentration, dyestuff concentration, and scavenger ion effects were investigated. It was reported that increasing scavenger anions decreased the reaction and removal rates. It was reported that 89% removal efficiency was obtained under optimum conditions (pH 3.0, [AY 17] = [Fe^{2+}] = 0.06 mM, and [H_2O_2] = 0.9 mM) in 60 minutes of reaction time (Khan et al., 2018).

It has been observed that advanced oxidation studies for AY 17 removal are limited in the literature. This study investigated the effects of ozone gas flow rate, ozone gas concentration, H_2O_2 concentration, and initial AY 17 concentration for ozonation and peroxane processes in a batch-operated bubble reactor for color removal from synthetic wastewater containing AY 17.

2. Materials and Methods

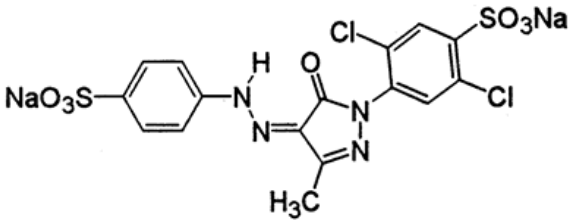
2.1. Chemicals and Analysis

The solid form of AY 17 dye used in the experimental studies was obtained commercially. The chemical structure and chemical properties of AY 17 with CAS registration number 6359-98-4 are given in Table 1. AY 17 was determined colorimetrically using a UV-VIS spectrophotometer (SpectroFlex 6600, WTW) at 403 nm wavelength. In the experimental study, 35% hydrogen peroxide was used. The pH measurements were measured using the WTW (3400i) brand multi-parameter; the experiments were carried out at the natural pH value of 5.7 and were measured and recorded throughout the experimental period. Color removal was calculated using equation 1, as shown below;

$$Removal\% = ((C_0 - C_t)/C_0) * 100 \quad (1)$$

C_0 represents the initial concentration of AY 17, and C_t represents the remaining concentration of AY 17 at time t.

Table 1. Chemical structure and properties of Acid Yellow 17

Commercial Name	Acid Yellow 17
Molecular structure	
Molecular Formula	$C_{16}H_{10}Cl_2N_4Na_2O_7S_2$
Molecular Weight	551.29 g/mol
Max. Wavelength	403 nm

2.2. Experimental Procedure

A glass reactor with a total height of 16.0 cm and an inner diameter of 6.5 cm was used in the experimental studies. Ozone was introduced into the system through a diffuser placed at the bottom of the reactor. The studies were carried out at ambient temperature (20 °C) without temperature control. The volume of the solution AY 17 used in the reactor is 500 mL, and the natural pH of this solution is 5.7. The schematic representation of the experimental system is given in Figure 1. Ozone gas was produced using dry air by electrical discharge. The air from the compressor used as an air source was first passed through the dust and moisture trap and then given to the ozone generator (Anseros, COM AD-08). The solution placed in the glass reactor was subjected to ozonation under the conditions investigated for 45 minutes, and samples were collected over time and analyzed for AY 17.

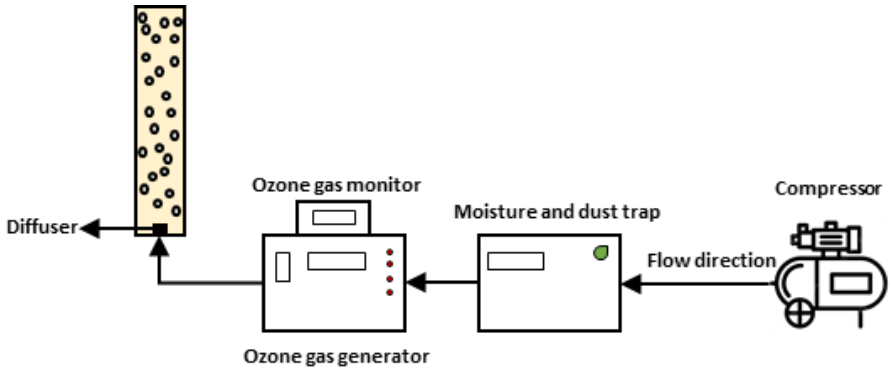


Figure 1. Schematic representation of the experimental system.

3. Results and Discussion

3.1. Effect of Gas Flow Rate on AY 17 Removal in Ozonation Process

To investigate the effect of ozone gas flow rate on AY 17 removal by ozonation process in a batch-operated bubble reactor, gas flow rates of 150, 200, and 250 L/h were tested. A 500 mL solution containing 200 mg/L AY 17 at natural pH (5.70) and ambient temperature (20 °C) was placed in the reactor, and 5.5 g/m^3 ozone gas was introduced through a diffuser at the bottom of the reactor. To examine the effect of gas flow rate, the color removal obtained as a result of ozonation for 45 minutes at different flow rates is given in Figure 2.

As seen in Figure 2, increasing the gas flow rate from 150 L/h to 200 L/h increased the removal efficiency. The increase in removal efficiency with increasing gas flow rate can be explained in two ways; i. the ozone gas mass supplied to the system will increase (W_{ozone}= C_{ozone}*Q_{ozone}) and ii. increasing the gas flow rate will increase the mass transfer rate. Increasing the flow rate will increase turbulence and mass transfer surface area. However, as seen in Figure 2, the removal efficiency has a negative effect when the gas flow rate exceeds 200 L/h. This effect can be attributed to two reasons. Firstly, an excessive gas flow rate will cause bubbles to coalesce, and mass transfer will be negatively affected. Secondly, when the increased gas flow rate increases the gas bubble velocity, it will cause the ozone molecules in the gas bubbles to leave the system without transfer. In other words, ozone molecules will leave the system without reacting with the dyestuff (Duong et al., 2022; M. Gao et al., 2012; Konsowa, 2003; Turhan et al., 2012).

3.2. Effect of Gas Concentration on the Removal of AY 17 in the Ozonation Process

Ozone gas concentrations of 5.5, 11, and 16.5 g/m^3 were used to study the effect of gas ozone concentration on the decolorization of the AY 17 aqueous solution. A 500 mL volume solution containing 200 mg/L AY 17 at natural pH (5.70) and ambient temperature was placed in the reactor, and ozone gas at a flow rate of 200 L/h was introduced through a diffuser at the bottom of the reactor. During the 45 minute reaction, samples taken over time were analyzed, and removal efficiencies were calculated and given in Figure 3.

As seen in Figure 3, increasing gas ozone concentrations increased the removal of AY 17. At the end of 45 minutes of reaction time, AY 17 removal efficiencies for ozone gas concentrations of 5.5, 11, and 16.5 g/m^3 were 80.5%, 89%, and 98%, respectively. Since increasing ozone gas concentrations cause an increase in ozone molecules given to the system per unit time, the removal efficiencies also increase. In addition, increasing ozone concentration in the gas phase will increase the ozone gas transfer as it will increase the concentration gradient, which is the driving force in mass transfer. This will reflect positively on dyestuff removal. However, this increase is not unlimited for process efficiency. Because after a specific value, the ozone molecule given to the system will leave the system without reacting and will have a negative effect on cost-effectiveness (Tehrani-Bagha et al., 2010; Tizaoui and Grima, 2011; Turhan et al., 2012).

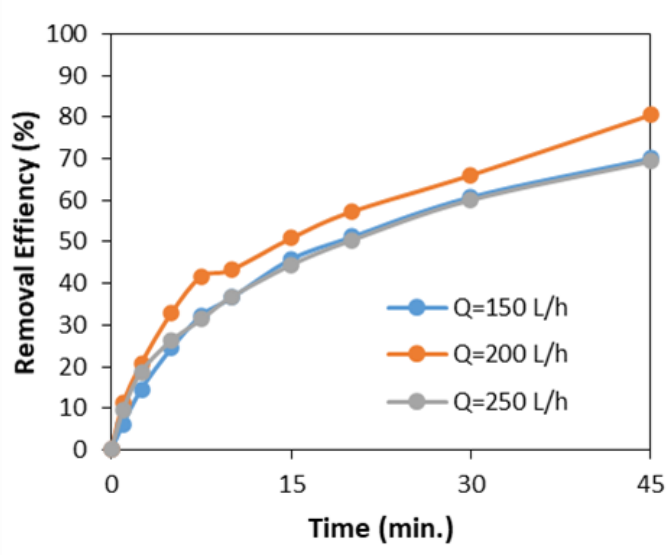


Figure 2. Effect of gas ozone flow rate on AY 17 removal.

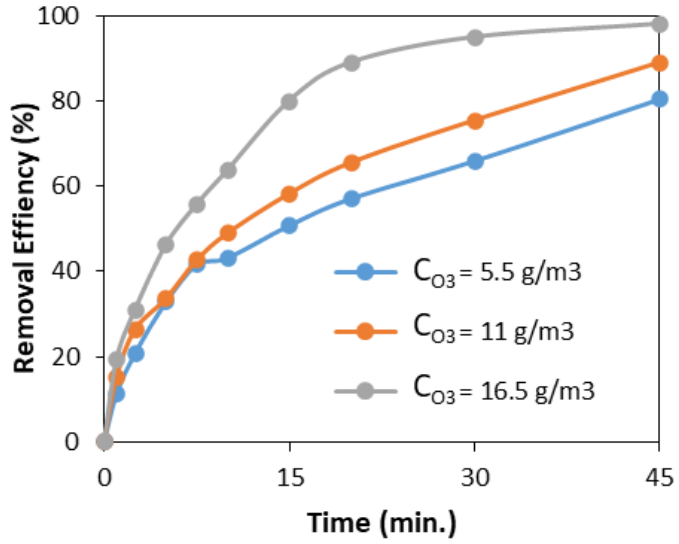


Figure 3. Effect of gas ozone concentration on AY 17 removal.

3.3. Effect of Initial Dye Concentration on AY 17 Removal

To investigate the effect of initial dye concentration on the decolorization of AY 17 aqueous solution, initial dye concentrations of 100, 200, and 300 mg/L were studied. At a gas ozone concentration of 16.5 g/m^3, natural pH (5.70), and ambient temperature (20 ^{o}C), 500 mL of solution was placed in the reactor, and ozone gas at a flow rate of 200 L/h was introduced through a diffuser at the bottom of the reactor. During the 45 minute reaction, samples taken over time were analyzed, and removal efficiencies were calculated and given in Figure 4.

As seen in Figure 4, it is clear that increasing dye concentrations decrease the removal efficiency and increase the decolorization time. Increasing dye concentration increases the dye molecule per unit ozone molecule. It increases the intermediate product concentration, which leads to a decrease in removal efficiency and an increase in decolorization time (Duong et al., 2022; Zhang et al., 2015). Tehrani-Bagha et al. reported that increasing initial dye concentrations decreased the color removal rate and increased the complete color removal time in RB 19 removal by the ozonation process. This is because the ratio of ozone molecules to dye molecules in wastewater will decrease with increasing initial concentration, and various intermediate products formed upon degradation of the leading dye will affect the color removal (Tehrani-Bagha et al., 2010). Similarly, there are studies suggesting that increasing dye concentrations will increase the color removal time (Konsowa, 2003; Turhan and Turgut, 2009).

3.4. Effect of Hydrogen Peroxide Concentration on AY 17 Removal

To investigate the effect of hydrogen peroxide concentration on the decolorization of solutions

containing AY 17, concentrations of 25, 50, and 62.5 mg/L H_2O_2 were studied. At a gas ozone concentration of 16.5 g/m^3, natural pH (5.70), and ambient temperature (20 ^oC), 500 mL of solution was placed in the reactor, and ozone gas at a flow rate of 200 L/h was introduced through a diffuser at the bottom of the reactor. During the 45 minute reaction, samples taken over time were analyzed, and removal efficiencies were calculated and given in Figure 5.

As seen in Figure 5, low hydrogen peroxide addition decreases the removal of AY 17 to a limited extent and does not affect the decolorization at increasing dosages. In the literature, although there is generally an improvement in dyestuff removal with the addition of hydrogen peroxide, the opposite is the case. The decrease or no effect on color removal with the addition of hydrogen peroxide can be explained in two ways. First, it may be due to the scavenging effect of $^{\bullet}OH$ radicals in an alkaline environment. Second, it can be said that the oxidation mechanism depends on the dye structure and is specific to each dye group (Bilińska et al., 2017; Muthukumar et al., 2005). Components in the dyestuff structure can affect the reaction rate with ozone or hydroxyl radicals. In a study investigating the removal of different dyes by various advanced oxidation processes (O_3, H_2O_2/O_3, and H_2O_2/O_3/UV), it is stated that the color removal performances are different for different mono azo dyes and that not only azo groups but also other structural properties of dyes are effective in the removal of dyes (Muthukumar et al., 2005).

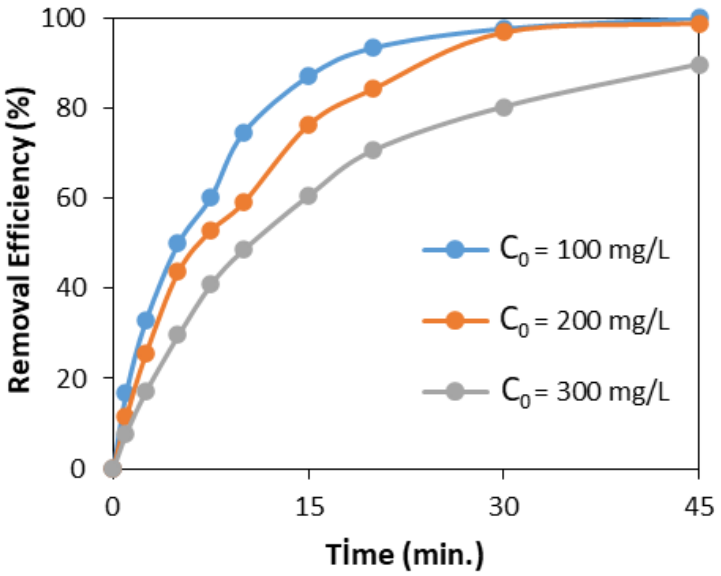


Figure 4. Effect of initial dye concentration on AY 17 removal.

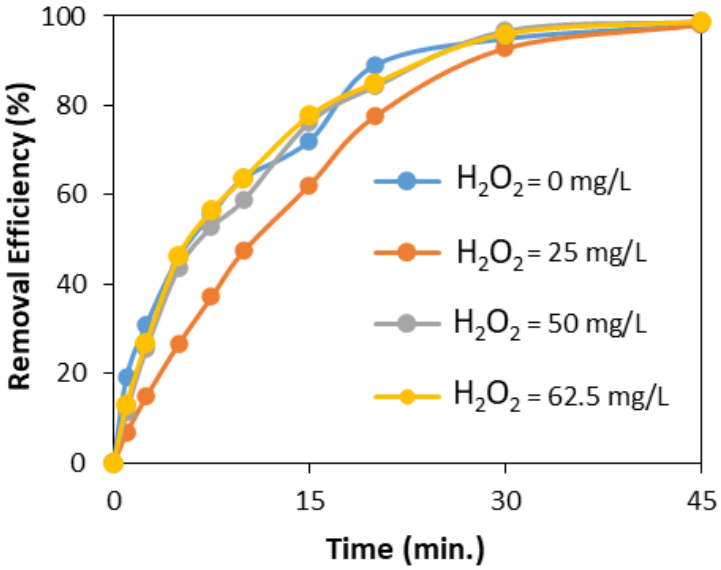


Figure 5. Effect of H_2O_2 concentration on AY 17 removal.

4. Conclusion

In this study, ozonation and peroxane processes were investigated in a batch-operated bubble reactor for decolorization in aqueous solutions containing AY 17 dye, and the parameters affecting the processes were investigated. The effects of ozone gas concentration, ozone gas flow rate, initial AY 17 concentration, and hydrogen peroxide concentration on color removal were investigated. Increasing gas flow rate and gas concentrations in the ozonation process increased color removal, but optimum values should be obtained for these parameters in terms of process efficiency and energy cost. The increase in gas flow rate will have a negative effect at a specific value depending on the system geometry and flow conditions. The increase in dye concentration decreased the removal efficiency. In real wastewater studies, the system can be operated effectively by changing gas ozone concentrations for changing dye concentrations. It is seen that the peroxane process is not effective for wastewater containing AY 17, while the ozonation process is quite effective.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	İ.C.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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THE EFFECT OF REGULARIZED REGRESSION AND TREE-BASED MISSING DATA IMPUTATION METHODS ON CLASSIFICATION PERFORMANCE IN HIGH DIMENSIONAL DATA

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Abstract: Missing data is an important problem in the analysis and classification of high dimensional data. The aim of this study is to compare the effects of four different missing data imputation methods on classification performance in high dimensional data. In this study, missing data imputation methods were evaluated using data sets, whose independent variables between mixed correlated with each other, for binary dependent variable, p=500 independent variables, n=150 units and 1000 times running simulation. Missing data structures were created according to different missing rates. Different datasets were obtained by imputing the missing values using different methods. Regularized regression methods such as least absolute shrinkage and selection operator (lasso) and elastic net regression were used for imputation, as well as tree-based methods such as support vector machine and classification and regression trees. At the end of simulation, the classification scores of the methods were obtained by gradient boosting machine and the missing data prediction performances were evaluated according to the distance of these scores from the reference. Our simulation demonstrates that regularized regression methods outperform tree-based methods in classifying high dimensional datasets. Additionally, it was found that the increase in the amount of missing values reduced the classification performance of the methods in high dimensional data.

Keywords: Gradient boosting machine, High dimensional data, Imputation, Classification, Simulation

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1. Introduction

Dealing with missing data is a crucial aspect of statistical analysis. In statistical studies, missing values occur when observations for a variable cannot be obtained due to various reasons (Jadhav et al., 2019). The presence of missing data is a common issue in clinical research and can significantly affect the data analysis process. Understanding the source and structure of missing data is crucial. Naive analyses, such as complete-case and available-case analysis, can cause bias, loss of efficiency, and unreliable results (Enders, 2022). When dealing with missing data, it is advisable to make use of any available partial information to estimate the missing values and analyze the complete dataset. This approach is more preferable than excluding the missing units from the analysis, as it helps to preserve the integrity and completeness of the data (Rubin, 1988; Little and Rubin, 2019).

Missing data, which negatively affects statistical analysis processes, is also an important problem for researchers dealing with classification problems in high dimensional data. When training a model, several commonly used classification methods are unable to deal with missing values in the training data (Deng et al., 2016). Therefore, it has become imperative to research and develop appropriate imputation methods for missing values in the training data to enhance the overall performance of the classifier on test data. Many of the methods that handle missing data are not suitable for high dimensional data because of their theoretical structure. Tree-based and regularized regression-based methods are remarkable in studies on missing values in high dimensional data (Yin et al., 2016; Zhao and Long, 2016).

The objective of this research is to assess the impact of regularized regression imputation methods, such as least absolute shrinkage and selection operator (lasso) and elastic net regression, and tree-based missing data imputation methods, such as support vector machine (SVM) and classification and regression trees (CART) on the classification performance by gradient boosting machine (GBM) in simulated high dimensional data.

2. Materials and Methods

In this section, we first described the theory of imputation methods and GBM structure. At the end of this section, we gave information about the simulation algorithm.

2.1. Regularized Regression Models

Regularized regression is a statistical technique that is quite similar to ordinary regression, whether it is linear or logistic. The main difference between the two lies in the fact that regularized regression adds an extra

constraint, which has the objective of shrinking the values of unimportant regression coefficients towards zero. This technique is particularly useful when dealing with high dimensional datasets. In such situations, regularized regression helps in avoiding overfitting, which can occur when the model is too complex and captures the noise present in the data. By shrinking the coefficients, regularized regression allows the model to focus on the most relevant predictors, thereby improving its generalization performance on new, unseen data (Przednowek and Wiktorowicz, 2013; Patil and Kim, 2020).

2.1.1. Lasso regression

Lasso regression is a technique used in linear regression to reduce the complexity of models when working with high dimensional datasets. The lasso regression, also known L1 regularization, works adding a penalty term to the cost function. This penalty shrinks some variable coefficients to zero, selecting only the most significant features, and induces a sparse solution (Breiman, 1995; Tibshirani, 1996).

2.1.2. Elastic net regression

Elastic net regression is a general regularization technique that combines L1 and L2 regularization techniques for feature selection and reduction. The regularization term L2, also known as Ridge regression, suggests keeping the coefficients small but not zero, which in turn reduces the coefficients of less significant features. Thus, some coefficients shrink to exactly zero, while others shrink towards each other. This allows for variable selection and reduces the complexity of the model (Zou and Hastie, 2005; Friedman et al., 2010).

2.2. Tree-Based Models

Tree-based models are a type of machine learning algorithm that can also be applied for high dimensional data and fall under the category of nonparametric models. These models operate by dividing the feature space into smaller, non-overlapping regions. The partitioning process is done in such a way that the response values within each region are similar to each other. Overall, tree-based models are a powerful tool for solving a wide range of supervised learning problems, including regression and classification tasks (Chang and Chen, 2005; Clark and Pregibon, 2017).

2.2.1. Support vector machine

SVM is a popular machine learning algorithm used for classification and regression analysis. SVM works by finding the best possible boundary that separates data points into different classes. It tries to maximize the margin between the classes, which is the distance between the boundary and the closest data points. SVM is particularly useful when working with high dimensional datasets and can handle both linear and non-linear data. It is also known for its ability to deal with noisy data and outliers (Cortes and Vapnik, 1995; Hastie et al., 2009).

2.2.2. Classification and regression trees

CART is a decision tree algorithm that can be utilized for both classification and regression tasks. The data is divided into subsets by this algorithm in a recursive manner, depending on feature values. This process continues until a stopping criterion, such as reaching a maximum depth or minimum number of samples per leaf node, is met. At each split, the algorithm determines the feature that can separate the data into various classes or produce the smallest residual sum of squares for regression (Breiman, 2017; Loh, 2011).

2.3. Imputation Algorithm for Dealing with Missing Data

Let's consider a data set X consisting of n rows and p columns, where each row represents an observation and each column represents a variable denoted by $x_1, \dots, x_p$. We assume that the first t variables have missing. We use the notation $x_{obs,j}$ to represent the observed components and $x_{mis,j}$ to represent the missing components for variable j where $n_{obs,j}$ and $n_{mis,j}$ represent the number of samples, respectively. The collection of $p-1$ variables in X, excluding x_j, can be denoted as $X_{-j} = (x_1, \dots x_{j-1}, x_{j+1} \dots, x_t, x_{t+1}, \dots, x_p)$. Let $X_{obs_j,-j}$ and $X_{mis_j,-j}$ be the components of X_{-j} that correspond to the complement data of $x_{obs,j}$ and $x_{obs,j}$ (Deng et al., 2016; Stekhoven and Bühlmann, 2012).

All the imputation methods employed in the study run based on a particular algorithm. The algorithm can be described as follows (Zhang, 2016; Zhang et al., 2021):

1. Sort X in descending order based on the amount of missing values.
2. Use mean imputation to make an initial guess for any missing values and update X matrix $(\acute{X})$.
3. Fit a model $\left(x_{obs,j} \sim \acute{X}_{obs_j,-j}\right)$.
4. Predict $x_{mis,j}$ using $\acute{X}_{mis_j,-j}$ and obtain $\acute{x}_{mis,j}$.
5. Update variable j of $\acute{X}$ $(\acute{X} \leftarrow \acute{x}_j)$.
6. Repeat steps 3-5 for $j = 1,2, \dots, t$.
7. Obtain ultimate imputed dataset $(\acute{X}^{new} \leftarrow \acute{X})$.

2.4. Gradient Boosting Machine

GBM is a type of machine learning algorithm that uses an ensemble of decision trees to make predictions. It is a powerful and popular method for both regression and classification tasks, and is known for its ability to handle complex datasets with high accuracy (Schapire, 2003; Tian et al., 2020). GBM algorithm works by iteratively adding decision trees to a model, with each subsequent tree focusing on the errors made by the previous tree. This allows the model to gradually improve its performance over time, leading to highly accurate predictions (Nawar and Mouazen, 2017; Zhang et al., 2019). Any arbitrary loss function $L(.,.)$ can be used here.

Let n and p indicate the number of observations and independent variables, respectively; $y_i \in R^a$ denotes the dependent variable value of each observation (a=1 for regression, a=2 for classification) and $\{(x_i, y_i) | x_i \in R^p, y_i \in R^a\}_{i=1}^n$ denotes the training set. According to (Elith et al., 2008) the GBM algorithm can be described as follows:

1. To begin, the weak classifiers must be initialized by solving the equation 1 below, where γ denotes the step size:

$$F_0(x) = argmin_\gamma \sum_{i=1}^{n} L(y_i, \gamma) \quad (1)$$

2. Starting from first iteration $m = 1$, and up to a maximum of *M* iterations for learning:

a. The pseudo-residuals is computed for $i = 1,2, \dots, n$ as follows (equation 2):

$$r_{im} = -\left[\frac{\partial L[y_i, F_{m-1}(x_i)]}{\partial F_{m-1}(x_i)}\right] \quad (2)$$

b. We need to train a new base model $h_m(x_i)$ using the revised dataset $\{x_i, r_{im}\}_{i=1}^{n}$. Then the parameter γ_m is defined to solve the optimization problem as follow (equation 3):

$$\gamma_m = argmin_\gamma \sum_{i=1}^{n} L[y_i, F_{m-1}(x_i) + \gamma h_m(x_i)] \quad (3)$$

c. At last, we get our final strong classifier (equation 4):

$$F_m(x) = F_{m-1}(x) + \gamma_m h_m(x) \quad (4)$$

2.5. Performance Evaluation Criteria

The performance of missing data imputation methods in predicting original values and their impact on classification was assessed using the area under the receiver operating characteristic (ROC) curve (AUC) and F1 score. AUC measures model separability, ranging from 0 to 1, with higher values indicating better performance. (Hanley and McNeil, 1982; Fawcett, 2006). The F1 score, which balances precision and recall, is particularly useful when false positives and false negatives carry similar consequences, with higher scores indicating a more balanced model (Tharwat, 2021).

2.6. Simulation

Statistical analysis of the study was performed using R software, version 4.2.3 (R Foundation for Statistical Computing, Vienna, Austria). Most existing MI methods rely on the assumption of missing at random (MAR), i.e., missingness only depends on observed data; our work also focuses on MAR. We set the sample size to *n*=150 and included *p*=500 predictors in simulated dataset. The dataset contains a binary outcome y, which is fully observed, and $X = (X_1, X_2) = (x_1, \dots, x_p)$. Firstly, a set of $p - 10$ independent variables denoted as $X_1 = (x_{11,}, \dots, x_p)$ were created by drawing from a multivariate standard normal distribution with a mean vector of $(0, \dots, 0)_{p-10}$ and the correlation matrix was defined as the absolute values of its all off-diagonal terms were a maximum of 0.7. We randomly selected 50 variables (X_s) from X_1. We also generated a separate group of 10 variables called $X_2 = (x_{1,}, \dots, x_{10})$ from a normal distribution $(X_2 \sim N_{p_2}(\mu_2, \sigma_2^2))$, where μ_2 is a linear combination of X_s and σ_2^2 is equal to 1.5. To produce a binary outcome, certain values were randomly generated and divided into two groups depending on whether they were below or above the median value. These values were generated from a normal distribution$(N_p(\mu, \sigma^2))$, where μ denotes linear combination of X and σ^2 is equal to 5. Then missing values with MAR mechanism were created in $(x_{1,}, \dots, x_{10})$, resulting in approximately 10%, 20%, 30%, 40% and 50% missing rates per variable. Thus, datasets with different missing rates were obtained. Missing values were imputed using lasso, elastic net, SVM and CART. To assess the classification performance of the methods, complete (reference) and imputed datasets were initially split into training and test subsets using a 70:30 ratio, selected randomly. The models were trained using training sets, while test sets were utilized to obtain AUC and F1 values of the models. Missing data prediction performances were evaluated according to the distance of these values from the reference. The processes were repeated 1000 times..

3. Results

The performance evaluation of the imputation models was done by AUC and F1 values. Performance metrics were calculated as median (25th – 75th percentiles) and presented visually using forest plots. Hence, the evaluation process identified the methods that exhibited comparable performance and generated results in proximity to the ones derived from the reference dataset.

The reference data set provided median values of 0.945 and 0.902 for AUC and F1 values, respectively. The imputed datasets had the following median ranges for AUC and F1: 0.945-0.946 and 0.900-902 for the 10% missing rate; 0.943-0.944 and 0.898-900 for the 20% missing rate; 0.931-0.940 and 0.884-897 for the 30% missing rate; 0.928-0.937 and 0.885-889 for the 40% missing rate; 0.903-0.927 and 0.857-880 for the 50% missing rate. The performance of imputation methods was also assessed based on their AUC and F1 values. The median ranges for these values were as follows respectively: for the lasso, 0.925-0.945 and 0.880-0.900; for the elastic net, 0.927-0.946 and 0.880-0.900; for the SVM, 0.903-0.945 and 0.857-0.902; for the CART, 0.908-0.945 and 0.868-0.898 (Table 1).

After evaluating the effectiveness of all imputation techniques, considering AUC and F1 values, it was noticed that, all methods demonstrated good performance and were very close to the reference at 10% and 20% missing rates. However, the performance of the methods began to decline after the 20% missing rate. The regularized regression models performed slightly better than tree-based methods at the missing rate of 30%. Although the performance of the SVM method did not change at the missing rate of 40%, the performance of other methods decreased. However, regularized regression methods maintained their superiority over tree-based methods. As the rate of missing data increased to 50%, the differences in performance between

regularized regression methods and tree-based methods became more pronounced, with the former being closer to the reference than the latter. As a result, the tree-based methods moved further away from the reference as the rate of missing data increased, while the regularized regression methods showed more robustness in handling the missing data and produced better results (Figures 1 and 2).

Hierarchical clustering analysis, based on AUC and F1 values for all missing rates, was applied to determine the relationships among the methods and which methods were close to the reference. As shown the dendrogram graph in Figure 3, it was observed that the lasso and elastic net methods clustered together with the reference. However, the SVM and CART methods have formed a distinct cluster, separate from the others (Figure 3).

Table 1. Classification performances of the imputation models according to varying missing rates

		Missing Rate				
	Method	%10	%20	%30	%40	%50
AUC	Reference	0.945 (0.916 - 0.970)	0.945 (0.916 - 0.970)	0.945 (0.916 - 0.970)	0.945 (0.916 - 0.970)	0.945 (0.916 - 0.970)
	Lasso	0.945 (0.912 - 0.970)	0.944 (0.914 - 0.966)	0.940 (0.909 - 0.966)	0.935 (0.902 - 0.964)	0.925 (0.887 - 0.955)
	Elastic net	0.946 (0.912 - 0.966)	0.944 (0.912 - 0.966)	0.940 (0.905 - 0.966)	0.937 (0.901 - 0.964)	0.927 (0.885 - 0.956)
	SVM	0.945 (0.913 - 0.970)	0.943 (0.911 - 0.966)	0.931 (0.897 - 0.958)	0.928 (0.888 - 0.958)	0.903 (0.854 - 0.939)
	CART	0.945 (0.913 - 0.968)	0.944 (0.911 - 0.968)	0.937 (0.904 - 0.966)	0.933 (0.897 - 0.960)	0.908 (0.865 - 0.946)
F1	Reference	0.902 (0.865 - 0.933)	0.902 (0.865 - 0.933)	0.902 (0.865 - 0.933)	0.902 (0.865 - 0.933)	0.902 (0.865 - 0.933)
	Lasso	0.900 (0.864 - 0.933)	0.900 (0.865 - 0.932)	0.897 (0.857 - 0.929)	0.889 (0.850 - 0.923)	0.880 (0.837 - 0.915)
	Elastic net	0.900 (0.864 - 0.930)	0.900 (0.864 - 0.931)	0.895 (0.857 - 0.929)	0.889 (0.852 - 0.929)	0.880 (0.837 - 0.913)
	SVM	0.902 (0.864 - 0.933)	0.898 (0.857 - 0.930)	0.884 (0.846 - 0.917)	0.885 (0.842 - 0.919)	0.857 (0.815 - 0.897)
	CART	0.898 (0.865 - 0.929)	0.898 (0.863 - 0.933)	0.895 (0.857 - 0.927)	0.889 (0.851 - 0.920)	0.868 (0.818 - 0.902)

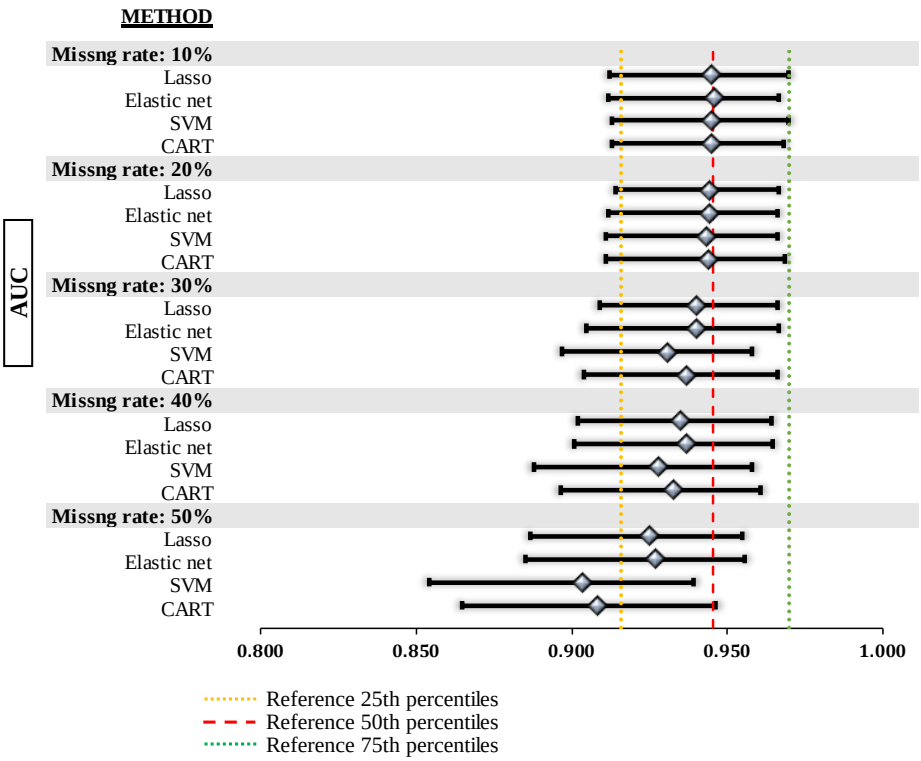

Figure 1. Forest plot that displays the AUC values of the methods.

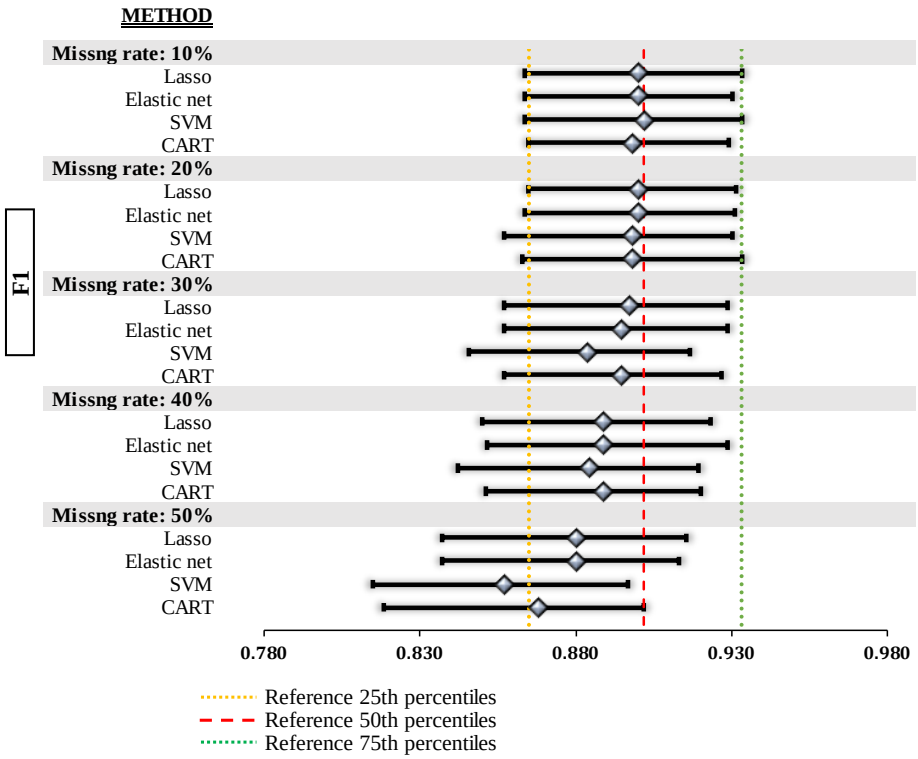

Figure 2. Forest plot that displays the F1 values of the methods.

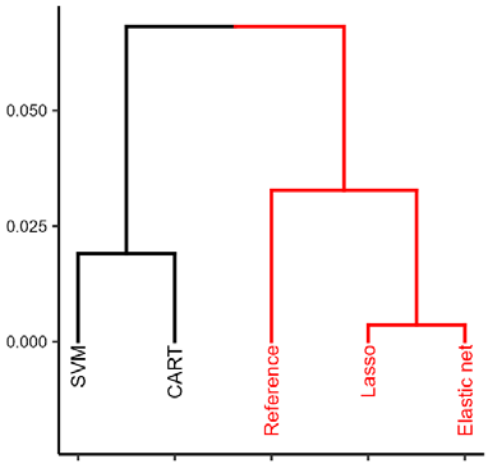

Figure 3. Dendrogram showing the relationship among the imputation models by AUC and F1 values.

4. Discussion

As the field of health continues to evolve, it is anticipated that accurate estimation of missing data will become even more critical to prevent information loss. As high dimensional data containing numerous patient details continue to increase, the incidence of missing data is expected to rise. Therefore, it will be essential to develop techniques to estimate missing data with minimum error to ensure that the models created with this data are as accurate and effective as possible. Schafer and Graham (2002), indicated in their study with real data that if missing observations are deleted from the data set, the statistical power decreases and erroneous inferences are obtained, especially as the missing rate increases. Therefore, it is recommended to use appropriate methods to handle missing data rather than simply deleting them from the dataset. Liu and De (2015), suggested that the foremost consideration in building an imputation model is to ensure compatibility, failing which, efforts should be directed towards enhancing the predictive accuracy of the imputation model.

The increase in the missing rate directly affects the effectiveness of imputation techniques. The higher the missing rate, the more challenging it becomes to impute the missing values accurately. Qin et al. (2007), showed that an increase in the rate of missing data decreased the accuracy of estimating missing values. Choudhury and Pal (2019), reported that the rise in the rate of missing data

has a detrimental impact on the effectiveness of imputation methods on classification performance, as also found in our study. Furthermore, in our study, although the change in the number of observations and the increase in dimensionality had some impact on the performance of the methods, it was observed that they did not alter the overall performance ranking. Therefore, fixed values for the number of observations and variables were used.

As known, choosing a proper method plays a crucial role dealing with missing data process. Since data structures vary in each dataset, the answer to the question "which method for which dataset" changes. Slade and Naylor (2020), conducted a comparison of the parametric and tree-based imputation methods in the MICE package of the R program. They performed this comparison on a simulated dataset for the regression problem. Their analysis revealed that both parametric and tree-based methods had similar error values and performance. However, the random forests method, which is one of tree-based methods, had the narrowest confidence interval as compared to the other methods. Lavanya et al. (2019), indicated that the lasso imputation method is a highly effective approach to address the challenges associated with missing data in high dimensional datasets. Peña et al. (2019), demonstrated using a real data set that imputation methods such as ridge and lasso, which are based on regularized regression, can estimate missing values with a very low error.

There are only a limited number of studies in the literature that examine the effect of missing data imputation methods on classification performance with different performance evaluation criteria. Liu et al. (2020), conducted a research study analyzing the impact of missing rate on the accuracy of classification. The study revealed that as the rate of missing data increases, the rate of correct classification decreases. Acuna and Rodriguez (2004), found that the imputation method did not significantly affect classification accuracy. However, in their studies, they only used basic and simple imputation methods and worked with datasets that had relatively small amounts of missing data (i.e., between 1% and 20%). Farhangfar et al. (2008), evaluated the effect of some tree-based imputation methods on classification performance on missing data sets with missing rates ranging from 5% to 50%. According to their report, when dealing with data with over 10% missing data, imputation methods tend to improve classification error more than simply ignoring the missing data. However, there is no universally accepted method which could be considered as the best. In our study, we examined the effects of imputation methods on classification performance in high dimensional data, unlike previous literature. Our study revealed that, at lower missing rates, there wasn't a notable variation in performance between the methods in terms of their impact on classification performance. However, as the missing rate increased, tree-based methods were observed to be less effective as compared to the lasso, and elastic net methods that are based on regularized regression. It was noted that these regularized regression methods performed better than tree-based methods as the missing rate increased.

5. Conclusion

In this study, the impact of various imputation methods on classification performance in high dimensional data was evaluated. Our simulation results indicate that regularized regression methods outperform tree-based methods in improving classification on high dimensional data. In the field of data analysis, there are various techniques employed to address the issue of missing data. However, certain methods may not be efficient in handling high dimensional data due to their underlying theoretical framework. As a result, it is crucial to carefully select the appropriate method to avoid information loss that is common in high dimensional data and to enhance the accuracy of predictive models.

Author Contributions

The percentages of the authors' contributions are presented below. The authors reviewed and approved the final version of the manuscript.

	B.V.	İ.K.Ö.	M.T.
C	35	35	30
D	40	40	30
S	10	45	45
DCP	50	25	25
DAI	30	50	20
L	25	25	50
W	60	20	20
CR	40	30	30
SR	45	45	10
PM	40	40	20
FA	50	30	20

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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INSURANCE SOLUTION FOR CLIMATE CHANGE: LEGISLATION ANALYSIS IN TÜRKİYE

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Abstract: In the light of changing and evolving parameters throughout the World, risk definitions vary as well, leading to the necessity to make new risk definitions in various fields in addition to those, the effects of which can be easily observed and measured, such as technology and information security. This change also manifests itself in the insurance industry based on climate change. The increase in the number and scale of climate-based natural disasters throughout the World, in conjunction with global warming, made the economic losses caused by natural disasters visible. Climate change A caused and will continue to cause significant changes in many fields of the insurance industry, such as property insurances, agricultural insurances, and health insurance. The insurance industry attempts to mitigate the negative impacts of climate change through active risk measures such as mapping, risk analysis, funding research, collective data sharing, and active participation in climate protection activities throughout the World. However, it is crucial for the State and affiliated public enterprises to support this process as a regulatory and adequate power, create a suitable legal, financial and regulatory framework for private sector initiatives, and conduct informative activities about the importance of insurance in natural disasters. Emerging financial burden should be divided between individual-public-private enterprises, and this division should be made in a balanced and fair manner in the light of the applicable legislation. This study primarily addresses the devastating impacts of climate change on the World and Türkiye, which emerged notably in the recent era and the financial burden brought about by this. Then the issue of responsibility of the public sector, which is responsible for taking necessary and adequate measures against climate change, was explored in the context of both national legislation and international agreements. The adequacy of the applicable legislation for the State and public enterprises to create a suitable consciousness-raising, a preventive and compensatory legal framework specific to the climate change in Türkiye was reviewed, and suggestions were made.

Keywords: Climate Change, Legislation, Insurance solution, Risk, Responsibility.

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1. Introduction

Climate change will have many knowable and unknowable effects on humanity in the upcoming years. Climate change is now a serious issue that affects are already has been observed in every country. Since almost everyone will be affected by climate change, there is a need for plans to increase the resistibility of humanity against the coming physical and financial impacts of changes. In addition, climate change increases the frequency and intensity of extreme weather events worldwide. Its effects on lives, livelihoods, and assets are not evenly distributed and threaten efforts to reduce poverty sustainably. Disasters force 26 million people into poverty each year. The cost of responding to disasters will continue to increase and force countries to divert longer-term development finance into short-term response measures frequently.

By 1995, countries launched negotiations to strengthen the global response to climate change and, two years later, adopted the Kyoto Protocol. Then, the 2015 Paris Agreement, adopted in Paris on 12 December 2015, marks the latest step in the evolution of the United Nations climate change regime and builds on the work undertaken under the Convention. The Paris Agreement charts a new course in the global effort to combat Climate Change. The Agreement also aims to strengthen the ability of countries to deal with the impacts of climate change. After thinking globally about climate change, we should focus on our region very well to be able to act locally first. Türkiye is one of the countries with a wide variety of climates and will be affected from different aspects. Due to its geographic location, both socio-economically and politically, Türkiye is a sensitive country that will be negatively affected by the possible side effects of global warming. Because of potential threats of its location, Türkiye is among the countries that will face problems arising from the climate change.

Therefore, how can the Turkish government and people increase the resilience against the climate change risks amongst the poorest and vulnerable people? Climate risk insurance comes into play at this stage. Climate risk insurance is a means of obtaining insurance against the

dangers of extreme weather events. What may be an incalculable drama for individuals or individual governments can become a calculable risk for the insured community. Climate risks insurance is gaining importance in and beyond climate negotiations and offers, many opportunities for improving climate risk management in developing countries. After the 2015 United Nations Climate Change Conference, Group of Seven (G7) countries at their summit in Germany, the leaders launched a new Initiative on Climate Risk Insurance (InsurResilience), pledging to bring climate insurance for 400 million currently uninsured individuals in developing countries by 2020. In many ways, the G7 initiative and the Paris Agreement are the culmination of a long process to establish insurance as an accepted climate adaptation instrument (Surminski et al., 2016). So that, we need to have a solid legal framework for any action.This research aims to analyze the adequacy of existing legislation in Türkiye by focusing on climate change insurance. It includes the study of physical and financial risks of climate change, especially in Türkiye, the international and local dimensions of Turkish government responsibility, and the study of exiting legal bases and solutions in Turkish legislation with providing a structure of successful samples of Turkish Natural Catastrophe Insurance Pool.

2. Materials and Methods

2.1. Climate Change Effects

How to respond to the damage caused by climate change continues to be asked in the scientific world. In addition, at the same time, the effects of climate change are increasing in the world while we are trying to establish various ways and methods. These climate change effects can be classified as physical and financial effects.

2.2. Expectative Physical Risks

The world is warming up. The Intergovernmental Panel on Climate Change (IPCC) forecasts a temperature rise of 2.5 to 10 degrees Fahrenheit over the next century. The IPCC predicts that increases in global mean temperature of less than 1 to 3 degrees Celsius above 1990 levels will produce beneficial impacts in some regions and harmful ones in others. Net annual costs will increase over time as global temperatures rise. The IPCC states, "The range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time.

Projections of future climate over the U.S. suggest that the recent trend towards increased heavy precipitation events will continue. More droughts and heatwaves. By the end of this century, what have been once-in-20-year extreme heat days (one-day events) are projected to occur every two or three years over most of the nation.

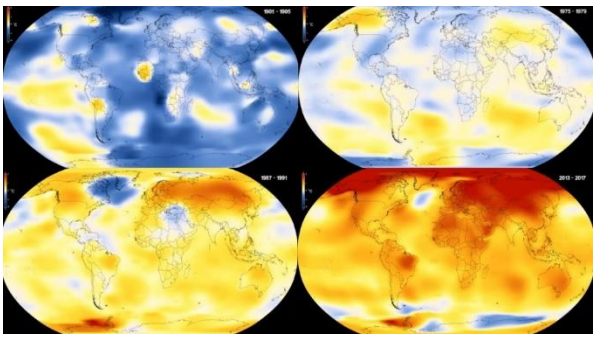

Figure 1. Temperature changes around the world from the year 1901 to 2017.

Hurricanes will become stronger and more intense. The intensity, frequency, and duration of North Atlantic hurricanes and the frequency of the strongest (Category 4 and 5) hurricanes have increased since the early 1980s. Hurricane-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm. Sea level will rise 1-4 feet by 2100. Global sea level has been increased by about 8 inches since reliable record-keeping began in 1880. It is projected to grow another 1 to 4 feet by 2100. This results from added water from melting land ice and the expansion of seawater as it warms.

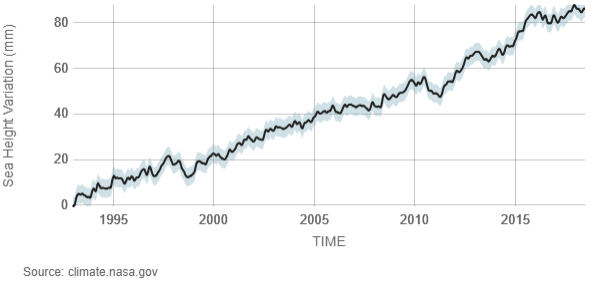

Figure 2. Global sea level from the year 1901 to 2017.

In addition, thousands of wildfires, large and small, are underway at any given time across the globe. Beyond the apparent immediate health effects, this "biomass" burning is part of the equation for global warming (Röder et al., 2024). In northern latitudes, wildfires are a symptom of the Earth's warming. Moreover, research suggests that a hotter Earth resulting from global warming will lead to more frequent and more extensive fires. The fires release "particulates," tiny particles that become airborne and greenhouse gases that warm the planet (Finneran and O'Sullivan, 2010).

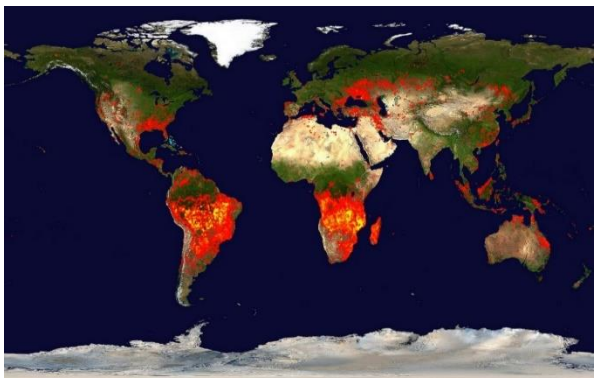

Figure 3. The moderate resolution imaging. Spectroradiometer (MODIS) on NASA's Terra satellite shows fires around the world.

In the local scale of this study, we will focus on Türkiye. In Türkiye, the annual temperature over the period 1961–1990 showed a trend of statistically significant warming over land in southeast Europe of approximately 0.4–0.6°C per decade. The statistical analyses of the Turkish temperature series over the period 1950–2006 showed a turning point in 1992 (1993). Following this year, annual temperatures began to increase gradually (Doğan et al., 2020).

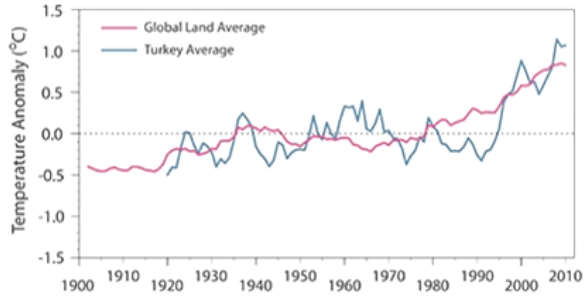

Figure 4. Average annual temperature in Türkiye from the year 1901 to 2010.

The below maps will show the model-estimated mean annual temperature distribution in Türkiye for three different periods, 1961-1990, 2041-2070, and 2071-2099. The temperatures range from about 18°C in the southern coastal areas to below 4°C in much of the high eastern plateau. As the comparison with the observed temperature shows, the simulated 1961-1990 temperature is relatively accurate. Comparing future maps with the 1961-1990 maps indicates that the temperature will increase all over Türkiye. The increases can be observed more clearly in the change maps of 1961-1990, 2041-2070, and 2071-2099 (Şen, 2013).

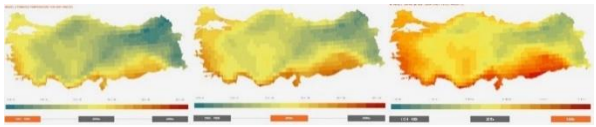

Figure 5. Model-estimated mean annual temperature distributions in Türkiye.

So, what are the results of the temperature increase in Türkiye? There is no comprehensive research that cans clearly shows the possible physical risks related to Türkiye. Authors reached different kinds of papers that evaluate climate risks separately, focusing on floods, sea rise, forest fires, etc. Since it is impossible to explain all the climate risks in this study, we have chosen forest fire as a sample. Because of the substantial amount of Turkish society in direct or indirect interrelating with forest-related events, we think that temperature increase will have huge effects on southern parts of the country, especially the Mediterranean region.

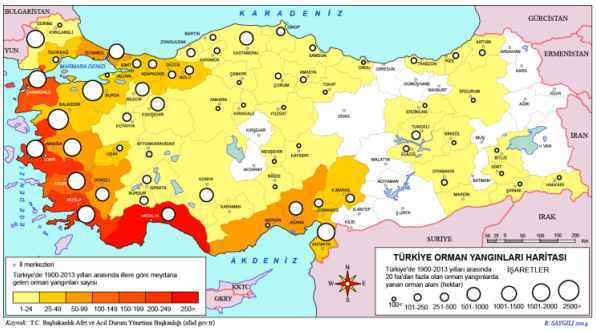

Figure 6. Distribution of forest fires in Türkiye between the years 1900 and 2013.

According to Alcamo et al. (2022) forest fire danger, fire season length, and fire frequency and severity are very likely to increase in the Mediterranean. Previous forest fire counts in Türkiye indicate that the forests along the Mediterranean, Aegean, and Marmara regions are already at high risk. The number of forest fires increases substantially on hot summer days when these areas, characterized by a typical Mediterranean climate, receive little or no rain. As the climate change projections indicate that the temperatures will continue to rise while rainfall decreases, we could expect more forest fires in these areas in the future. The areas with fewer fires may also be subjected to more forest fires in the future. It will be complicated to sustain the present forest cover, especially in the southern and western parts of Türkiye, when the air gets warmer and dryer (Şen, 2013).

Expectative Financial Risks

The first effects of climate change are caused by temperature rises and fluctuations in the precipitation regime. Extremities in these climate elements cause severe economic losses by increasing the frequency and severity of climate-related natural disasters such as drought, flood, and storm. Approximately 87% of natural disasters experienced during the 1980-2012 period are natural disasters caused by climate. The economic loss caused by these natural disasters in the same period was approximately $ 2.8 trillion. When analyzed on an annual basis, this FIGURE corresponds to $ 85 billion. These economic losses caused by climate change are estimated to be around 1 trillion dollars per year in 2050, people (Hallegatte et al., 2014) In addition, in another study in the USA costing out the effects of climate change,

Episodes of severe weather in the United States, such as the present abundance of rainfall in California, are brandished as tangible evidence of the future costs of current climate trends. Figure 5 shows the estimated total direct damage to the US economy per year in response to global mean temperature changes (Hsiang et al., 2013).

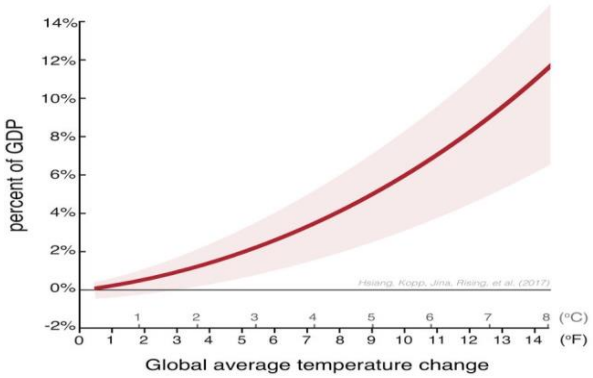

Figure 7. National average economic damage in USA.

In the local scale of this study, we need to focus on Türkiye. However, after studying the global literature about the financial risks of climate change, we may state that still there is no detailed risk assessment in most countries, including Türkiye. Nevertheless, according to Hsiang et al., research in 2017, the average 2 °C of increase in temperature will damage approximately 1.5 % of the Gross domestic product (GDP) in the USA. So, since there is no clear assessment in Türkiye, if we extend this estimation of USA data to Türkiye, to reach out at least a general overview for upcoming years, Türkiye with a GDP of 851.1 billion USD in 2017, will face with estimated financial damage of 12.7 billion USD. The point is that the mentioned cost may happen if the world conforms to the Paris Agreement. So, more than the Paris Agreement goals, the more temperature increase means more damages to GDP of countries.

3. Results and Discussion

3.1. Is The Insurance Sector Responsible For Losses Resulting From Climate Change?

Increasing the frequency of global warming and disaster incidents worldwide force insurance companies to identify areas that are sensitive to disasters, create significant risk areas, determine the measures to be taken against risks, and meet the damages of the insured after the disaster, and so on. Have undertaken essential tasks. In addition, some countries provide partial or complete governmental support to ensure insurance companies in areas with high risks (Türkeş and Deniz, 2010). The insurance industry is a critical part of the solution. It is neither the polluter nor the climate policy setter, but it plays a crucial role in building socio-economic resilience and enabling economic development and entrepreneurial pathways for achieving climate change goals and targets. The industry contributes significantly to creating financial stability to extreme events and other physical risks by providing risk information and risk pricing expertise, offering innovative risk transfer products and services, and improving the distribution channels and payout mechanisms (Golnaraghi, 2018).

In this context, the role and importance of risk reduction must be emphasized, and where possible, the underlying risks and associated drivers must be proactively reduced. Insurance and risk-transfer instruments become most effective and efficient when addressing residual risks that cannot be eliminated. More intensive risk-reduction efforts alongside risk finance strategies focusing on expanding insurance markets in emerging economies are urgently needed. Indeed, growing evidence shows that countries with greater penetration of insurance coverage experience faster economic recoveries from disasters and rebuild with greater resilience to future disasters. A 1% increase in insurance penetration reduces the disaster recovery burden on taxpayers by 22% (Madeleine et al., 2018).

The political commitments coming from the Group of Seven (G7) and the Paris Agreement have been supported and welcomed by several insurance companies and industry initiatives such as the Munich Climate Insurance Initiative, Climate Wise, and the Geneva Association (Alcamo et al., 2022) But, since natural disasters' damages and physical losses are large, the insurance sector and the government undertaking the risks together in most countries. For Instance, in France and Spain, natural disaster insurance is under statutory and unlimited governmental insurance. In the USA, the state is directly responsible for the flood risk. In Switzerland, natural disaster insurance is mandatory in policies. However, the state does not provide a definite guarantee. In this regard, insurance companies have developed joint programs (Acar, 2006).

In Türkiye, failure to establish the whole meaning of the insurance conditions, the most significant realization of expected risk and not enough pool of policyholders, poses obstacles to providing appropriate insurance coverage rates and forcing the state's annual budget to separate a great source against natural disasters. Therefore, it would be fair to develop a state-funded insurance system against natural disasters in Türkiye. Türkiye has enough experience in this aspect. In 2005, a state-supported agricultural insurance development strategy was implemented in Türkiye to reduce the impact of natural disasters on the farm sector and to transfer risk, which TARSİM manages. As of 1 January 2010, the risk of floods has been included in the scope of the state-supported agricultural insurance. Moreover, a successful co-operative example of private and governmental collaboration is compulsory earthquake insurance introduced under the Turkish Natural Catastrophe Insurance Pool (DASK) in Türkiye due to country earthquake features and reduced earthquake risk (Çekici, 2009).

Therefore, considering the examples around the world and Türkiye, it is clear that the Turkish government and private sector cannot be responsible independently for climate-related disasters. A good plan needs the collaboration of the private sector and governmental bodies together. However, before any action, we should consider the legal basis. Afterward, we will analyze the sufficiency of current Turkish legislation regarding climate disasters.

3.2. Climate Change in Turkish Legislation

The issue of climate change in Turkish legislation has gain importance in the last 15 years, and even no mainframe law has been introduced so far, many current provisions of the law are considered in this direction.

To dive into the topic of the work, administrative liability, firstly, the legislations concerned are analyzed. To detect public liability in the destructive effects of climate change in persons and institutions, firstly, the legal qualification of the topic should be made. After defining and qualifying climate change from a legal perspective, it would be easier to detect liability.

3.3. Legal Analysis of Climate Change

Definition of climate change from a legal perspective is vital for detecting the precautions that should be taken, responsible persons and institutions, the conditions for the civil and criminal liability, possible sanctions and rules, and supervision procedures. If climate change is defined only as a part of environmental law, a scientific and technical term, protection of the persons and institutions that get affected by climate change would get more challenging, the legislation concerned would stay unclear and dispersed.

Therefore, due to the analysis and evaluation of Turkish legislation, climate change is qualified as a "disaster," and as a result of such qualification, the State's liability is analyzed.

3.4. The Concept of Disaster in Turkish Legislation

There are different definitions of the concept of disaster in the literature, mainly on similar criteria.

"The incidents which cause physical, economic and social loss, stops or suspends the course of daily life and human activities," "the incidents which rises relatively unexpectedly and suspends the public life," "the incidents which negatively affects the humans, infrastructure, and environment in a large scale," "the incidents which cause intense damage, harm, and destruction.", "The fact that victims of disasters are humans or disasters cause loss of lives marks the concept of disaster as a social fact." "Disaster is called as "disaster" because, as a result, it ruins or suspends human life. Without these factors, as a result, it should not be defined as "disaster" but "natural event," "… [Disasters are the incidents which] is impossible for the society to overcome by its sources, which causes a serious loss on humans and the environment, destroys the social functions severely. [Disaster] arises out of the natural events (fire, flood, earthquake, storm, etc.) or human negligence; it is either the fact or the possibility of the occurrence of either extensive or severe or both extensive and severe damage, disability, loss of life and property."

To have one primary definition of disaster, the most extensive definition accepted by the United Nations is as following all the natural, technological-driven, or human-driven events, which cause a physical, economic, and social loss for humans affects the society by stopping or suspending the daily course of life and overwhelms the local capacity.In the light of the definition made by the United Nations, the definition of disaster in Turkish legislation was searched, but no concrete legal description is found. Instead, to define disaster, concerning pieces of law; different types of disaster, such as earthquake, fire, flood, soil creep, rockfall, snowslide, and settling, are mentioned; thus, the counting method is preferred. However, in the Article 31/b of Law No. 5902 (Law of the Establishment of AFAD) the institution responsible for disaster management, founded in 2009, Defines "disaster" in the legislation. This definition must be entirely comprehensible with the definition made by the United Nations. In the mentioned article, disaster is defined following: "the natural, technological-driven or human-driven events which cause a fully or partially economic and social loss on society and suspend or stop the course of daily life and human activities." (AFAD, 2014). Apparently, the sole definition is not enough to reflect the qualification of the concept. Types of disasters are classified due to their definition in the literature. According to that definition, disaster is defined as natural, technological-driven, or human-driven events. In the literature, although some scientists define the concept of climate change as a disaster, some views consider climate change as a process leading to disasters. Because of the temperature increase, a result of climate change, carbon emission may cause breathing problems; and again, as a result of temperature increase, lack of rainfall causes drought. One reason for disasters such as floods, snowslides, fires, and whirlwinds is climate change. The change in the dates of midseason, increase of the numbers of storms and hurricanes, decrease of water resources due to the increase of the rates in drought and aridity, change in flora, negative impacts on atmospherical activities, glacial melting is disasters caused by climate change.

Natural disasters may increase or decrease climate change, as climate change triggers natural disasters. Therefore, it is possible to consider climate change as a cause and result; it is not wrong to define every incident as a disaster.

After these definitions, all the planning, legislative regulations regarding climate change, detection of institutions and organizations are evaluated under disaster management.

3.5. Administrative Liability

All activities regarding disaster management are public service. Therefore disaster management systems fall under administrative law.

1982 Constitution of Turkish Republic rules that "the acts and operations of Administration shall never be

exempted from judicial review." The legislation clearly states that the administration is responsible for conducting the necessary study, research, control, governance, and supervision regarding disasters. The liability of administration means to compensate the sufferer's loss caused by the administration by transferring some of its asset wealth to the asset to the sufferer. If the administration doesn't pay for the loss by itself, compensation is made through the judiciary. The liability of the administration covers the civil and administrative liabilities of the administration.

3.6. Civil Liability of the Administration

Civil liability is the administration's liability regarding the conflicts that fall under private law and is heard before civil courts. In this scope, the loss is compensated according to private law provisions. Because civil liability falls under private law, it is not included in this work.

3.7. Administrative Liability of the Administration

The administration's liability means compensating the sufferer's loss caused by the administration by transferring some of its asset wealth to the asset to the sufferer. If the administration doesn't compensate for the loss by itself, compensation is made through the judiciary. In administrative law, the administrative liability of administration includes two main titles; these are "fault liability" and "strict liability" In the Constitution (Art. 125), even it is stated that the administration is responsible for its every act and operation; it falls under the responsibility of the judiciary to decide on substantive issues of the liability(Yıldız, 2023).The core of the fault liability is service failure. Service failure is defined as "a gap, defect or malfunction in the foundation, organization or operation of the administration" In Turkish Law, "nonfunctioning," "late functioning," or "malfunctioning" of the service are characterized as service failure. In these cases, the administration is obliged to compensate for the emergent loss.Not functioning of the service occurs when the administration does not act in fields it has the responsibility to act. To hold the administration liable for nonfunction, the administration should be entitled to and responsible for conducting the service concerned. No doubt, the administration cannot hold accountable for the nonfunction of any public service in areas where it does not have the responsibility to perform public service. Service failure occurs, and the administration holds liability from nonfunction in cases where administration holds conditional liability. However, if the administration is granted the power of discretion for conducting a service, an investigation is necessary to decide whether service failure occurs or not. Late functioning points out the service failure when the administration acts extraordinarily slow, and harm occurs due to this late functioning. However, it is not easy to prove that the administration provides service slowly or does not act fast enough. If the duration to provide a specific service is regulated in law, it is easy to detect whether the service is provided late or not. In that case, if the administration extends the period without a legitimate excuse, service failure occurs. But, if there is no provision in the legislation regarding the deadline, the beneficiants shall wait for the administration's action for a reasonable time. If the administration does not provide service in a reasonable time, service failure occurs.

Another subheading of administrative liability is "strict liability." As mentioned above, the main rule is to hold the administration liable for an emerged loss; the administration shall have the fault. In another term, if the administration does not have a weakness, it does not have a liability. However, regarding social, scientific, cultural, etc., transformations, fault doctrine is considered insufficient to compensate for the losses. Parallel to the social, economic, cultural, and scientific developments, the expectations from the state have risen, and with the acceptance of social state doctrine, the amount of the duties of the state has increased. That increase caused the possibility to harm the persons during the conduction of the administrative actions. Therefore, seeking for the administration's fault in every single case may preclude the compensation of the losses of persons. For these reasons, not to violate the rights of persons, the administration can be held liable if the causal link between administrative action and the loss exists; even the administration does not have the fault.

Strict liability can be defined as following: The administration can be responsible for compensating for the loss if the causal link between administrative action and the loss exists; even the administration does not have the fault. Strict liability is a particular type of liability. In administrative law, fault liability, namely service failure, is the basis for liability.

When the loss occurs, firstly, the existence of the service failure shall be investigated. If there is no service failure, then compensation of the loss based on strict liability might be possible. It is not possible to hold the administration liable based on both fault and strict liability. In general, strict liability is based on two main principles; the first one is "danger" or "risk," the second one is "equal apportionment of public burdens."

In the literature, according to the risk doctrine, which is also called risk-liability or harm theory, the administration is liable to compensate for the emerged loss. If the persons get harmed because of the endangering actions or means of the administration, even it does not have the fault. The principle of equal apportionment of public burdens points to the liability of the administration to compensate for the loss of persons who suffers more loss than others, even in cases the administration does not have any fault or perform any dangerous act. The raison d'être of the administration is to maintain public welfare. To keep this, the administration serves in different ways. Many persons benefit from these services. In some cases, services which are for the benefit of society may be harmful. Harmful to the rights of some of the community. In that case, the private loss of persons is compensated according to the

principle of equal apportionment of public burdens. Thus the balance, which had distorted against the persons who suffered the loss, is maintained. It is not possible to compensate for the loss based on both the fault and strict liability. Therefore, considering the course of the incident, the qualification of the loss shall be examined in detail, and the liability of the administration shall be detected whether it is strict liability in cases there is no service failure or not. Compared to fault liability, strict liability is a secondary type of liability." If misconduct causes the loss, fault liability occurs. But if fault liability does not happen but the loss does, and this situation harms the sense of justice, the administration holds strict liability. Because strict liability occurs in exceptional cases, it requires a literal interpretation. That shows that strict liability is a subsidiary type of liability. In administrative law fault liability comes before strict liability. In the scope of strict liability, the sufferer does not have the burden of proof regarding the administration's fault. And even the administration proves that it does not hold the fault, it does not remove the liability from itself. It is enough to confirm that the lien of causality between administrative phenomenon and loss exists. Strict liability is beneficial for the persons because it does not affect "the act of the third party" and "unexpected cases" Even these two elements occur, the administration keeps liability. But, if the "fault of the sufferer" or "force majeure" occurs, the administration does not be liable anymore. In some cases, it is possible for the administration not to hold liable partially or wholly. In other words, the lien of causality between the loss and administrative act may be weakened or disappear because of some cause except administrative actions or operations. In correlation with the removal or weakening of the lien of causality, the responsibility of the administration weakens. The reasons, which may remove or weaken the liability of the administration, are as follows: a force of majeure, unexpected cases, an act of the sufferer, and an act of the third party. The liability of the administration is limited to its technical and financial power. It retrieves the loss in its technical and financial capacity.

3.8. The Liability Regarding Climate Change

As mentioned above, administrative liability is divided into different sections, thus, different procedures and principles. Beyond any doubt, when it comes to administrative liability, fault liability must be sought in the first place. The administration shall be liable for the loss of late functioning, non-functioning, or malfunctioning of the service. In another term, to step out of the liability, the administration shall conduct necessary research, work, controls, supervision, and more importantly, provide educational programs, inform and raise awareness in advance. Regarding climate change, it is not possible to say that the Turkish state conducts such works. Due to the importance of the issue and the high possibility of being affected by climate change, mainly because of the country's location, the state is supposed to complete the works, which will help it eliminate or minimize the occurrence of administrative liability. Likewise, what is shown through scientific data is that Türkiye will come across more destructive effects of climate change more intensely. Therefore it is not easy to guess that in case persons seek the state's liability, the state would be liable in terms of the fault responsibility.

Even the state would take every possible precaution and conduct all technical works based on scientific, legal, research, and development actions; the state would be liable in terms of strict liability because of holding state power. In other words, the state is liable based on climate change because it has a legislative, judiciary, and executive power. This responsibility, which seems to be on the state's side, must be shared with persons by giving them some responsibilities. Because of the state's liability, payment of compensation occurs under a responsibility granted to persons. The state lays the obligation to its citizens in cases of disaster. One of these responsibilities is "to be insured" against the risks of disasters. In that case, the costs of the result of disasters caused by climate change would be paid by the insurance company. If the foreseen danger would take place, the insurer bears the consequences. On the contrary, the person who insures their interest or life pays money (premium). Insurance is not an ordinary commercial activity but an activity with economic and social functions. To function well and obtain its goals, insurance needs to become widespread; to spread insurance, it needs to be believed in. Therefore, the persons and the institutions working in the insurance industry shall be introduced to some rules and controlled by the state regarding the compliance to these rules; the insurance relation must be secured, and the main principles shall be determined (Gürsel, 2018). There is an insurance system for natural disasters in Türkiye, and it is being applied successfully since 2000. In Türkiye, as a country located on the seismic belt, the Law of Disaster Insurance is into force. According to this law, against earthquake, which is one of the disasters, persons are obliged to be insured to compulsory insurance for the earthquake (DASK), and persons who are not insured shall pay compensation and shall not receive any support. In that way, the state created a system that shared its responsibility with the person's responsibility. According to the concerned article, the state's liability ends in case the persons are not insured. Checking the Law of Disaster Insurance, the first article defines the purpose of the code as follows: *"..regulating the procedures and the principles regarding the insurance and reassurance warrants on the compulsory earthquake insurance made to compensate the possible material harms occurred in the buildings in case of earthquake and material and physical harms caused by the disasters and certain risks against which is not possible to be insured or granted warrant by insurance companies.".*

Even the code's title is Law of Disaster Insurance, the third article of the Lode mentions an institution named

Natural Disasters Insurances Authority, which is a legal entity. The Authority, founded under the Ministry in which the Undersecretariat of Treasury is connected, has the responsibility to grant the insurance and reassurance warrants according to the mentioned code. Mentioning the concept of "natural disaster," which is not included by the code's title, is correct and can be taken into account connecting to climate change. Because this Lode aims to regulate the procedures and the principles regarding the insurance and reassurance warrants on the compulsory earthquake insurance made to compensate the possible material harms. occurred in the buildings in case of earthquake and material and physical harms caused by the disasters and certain risks against which is not possible to be insured or granted a warrant by insurance companies. In Article 7/2 on the Code, it is stated that "..If the insurance companies do not grant warrants, in disasters such as earthquake, flood, landslide, hurricane, hail, frost, snowslip, etc.; it is possible to grant insurance or reassurance warrants according to insurance principles". To read the sentences; "material and physical harms caused by the disasters and certain risks against which is not possible to be insured or granted a warrant by insurance companies." and "In case the insurance companies do not grant warrants, in disasters such as earthquake, flood, landslide, hurricane, hail, frost, snowslip, etc." together, even the climate change is not clearly stated, the risks and the concept are parallel to the wording of the articles. Therefore, the most logical system is not creating a new system but using the current and well-working insurance system.

Changing the name of the code from Law of Disaster Insurance to Law of Natural Disaster Insurance and adding the wording "climate change" directly to the code, which the interpretation can already find, would be the more specific solution, and there is no legal hinder against it.

3.9. Model Propositions for Climate Change Insurance

Natural Disasters Insurances Authority, founded by Disaster Law in 2000, is a legal entity responsible for promoting, applying, and directing the Compulsory Earthquake Insurance in Türkiye.

The Compulsory Earthquake Insurance insures the property owners against earthquake risks and the fire, explosion, landslide, and tsunami caused by an earthquake. Regardless of the property's condition, it compensates for the loss and assists the return to everyday life.

DASK aims to promote the Compulsory Earthquake Insurance and spread it countrywide via the insurance companies, its agencies, and cooperating bank branches in cooperation with it and helps people to obtain this assurance with low premiums. DASK insurance gathers different components of the issue and creates an effective and easy procedure.

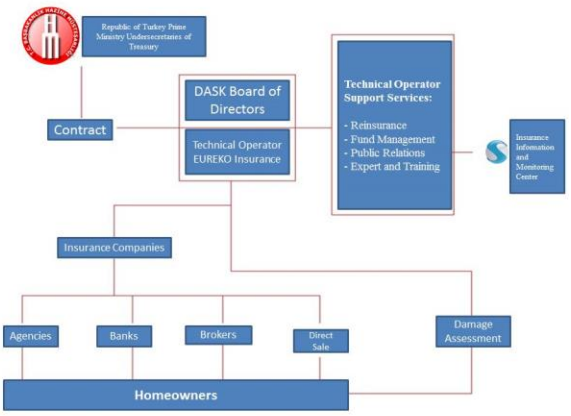

Figure 8. DASK component and procedures.

DASK has one Board of Management and is managed by it. The Board consists of one member from the under secretariat, Ministry of Environment and Urban Planning, Prime Ministry Disaster and Emergency Management Presidency and The Capital Markets Board, minimum on deputy general director level; one member selected among three candidates offered by Union and the Council of Higher Education and one member representing technical operator.

Looking at the Board of management, it can be seen that almost all the actors are involved in the council. Considering that this council would be responsible for climate change, a couple of light touches would cover this responsibility.

The Board of management consists of

A member from the Undersecretariat

A member of the Ministry of Environment and Urban Planning

A member from the Prime Ministry Disaster and Emergency Management Presidency

A member of the Association of the Insurance and Reinsurance Companies of Türkiye

A member of the Council of Higher Education

A member of the Capital Markets Board.

The core of this structure complies with climate change as well. Adding one more member who can inform and analyze, provide necessary information to the Board would be sufficient. Because in the Art. 7 of the Code "… for the earthquake, flood, landslide, hurricane, hail, frost, snowslip, etc.; in case it would be considered as necessary in regard with public welfare.." "for now; for the disaster of climate change, the condition "considered as necessary in regard with public welfare.." should be taken into consideration. Firstly, the wording "considered as necessary regarding public welfare.." shall be removed from the Code. Because every action taken before the existence of the disaster or/and the compensation of the loss caused by the disaster are for the public welfare in their nature, and it would be only time loss for the Board to examine whether such activities are for general interest or not. The actions that fall under the State's responsibility protect public welfare

by their nature, which is the main principle of public law.

Apart from this, the member whom the Council of Higher Education appoints should be appointed regarding the topic. It is necessary and enough to have one member who knows the technical aspect of climate change, or the Board shall be granted authority to appoint. This member can conduct a work; evaluating the cases individually, whether classified as a disaster, through reporting in advance and connecting the topic with climate change by analyzing the scientific information and analysis conducted through years. In that way, keeping the Board's structure, the climate change topic would be included in DASK, and solid progress would be made.

4. Conclusions

Climate change causes physical and economic harm. Because of climate change, carbon emission may cause breathing problems; and again, because of temperature increase, lack of rainfall causes drought. One reason for disasters such as floods, snowslides, fires, and whirlwinds is climate change. Additionally, the difference in the dates of the midseason, an increase of the numbers of storms and hurricanes, decrease of water resources as a result of the rise of the rates in drought and aridity, change in flora, negative impacts on atmospherical activities, glacial melting is disasters caused by climate change. Türkiye is in the climate change zone, and its future is under threat regarding all these negations.

As climate change causes natural disasters, natural disasters trigger or decrease climate change. Therefore, climate change should be qualified as a disaster. All the actions taken for disaster management are public service. Therefore, disaster management services are considered under administrative law, and the state's liability regarding disasters is crucial. The liability, which seems to fall under the state's liability at first glance, shall be shared with people by granting them some responsibilities. Therefore, in these issues, persons are liable, and state responsibility to persons regarding the disaster, and one of these responsibilities is being insured.

Regarding the topic, the legislation in Türkiye is sufficient, and there is an insurance system against natural disasters in Türkiye; and it is operated quite successfully and regularly. In Türkiye, which is on the constant seismic belt, the Code of Disaster Insurance is in force. This Code regulates the procedures and the principles regarding the insurance and reassurance warrants on the compulsory earthquake insurance made to compensate the possible material harms occurred in the buildings in case of earthquake and material and physical damages caused by the disasters and certain risks against which is not possible to be insured or granted a warrant by insurance companies. It should be applied for the disasters out of earthquakes as well; currently, the practice is not sufficient in this aspect. The DASK system is a well-functioning system that divides responsibility equally. It can be practiced for climate change as well. About this topic, information and education should be provided. The scope of the insurance must be broadened and become compulsory as compulsory earthquake insurance.

But in the first phase, a low amount of premium should be demanded, and the state shall handle this responsibility seriously. The burden of the state shall be more comprehensive because of the functioning of the state (in execution, judicial and legislative level), the deficiency in the direction, supervision of the environmental actions, the undeniable effect of the ecocide, the dimensions of the pollution by the economic activities as well as classifying it as a natural disaster.

Unlike the earthquake, climate change is not a field in which the personal liability or the precautions taken at the individual level would work and the state's responsibility, both at the national and international levels, has great importance.

Relevant people should be included in the Insurance Board of Management.

Regarding this topic, Turkish legislation is ready and eligible. There is no hinder to use the current legal and institutional structure for climate change.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	A.A.	N.V.	M.C.G.
C	40	30	30
D	40	30	30
S	40	30	30
DCP	40	30	30
DAI	40	30	30
L	40	30	30
W	40	30	30
CR	40	30	30
SR	40	30	30
PM	40	30	30
FA	40	30	30

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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BOROFENİN Si/SiO_2 SUBSTRATINA KİMYASAL BUHAR BİRİKTİRME YÖNTEMİYLE DİREKT OLARAK SENTEZLENMESİ VE ANALİZİ

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Özet: Bu çalışmada, borofenin doğrudan Si/SiO_2 alt taşı üzerine kimyasal buhar biriktirme metodu (KBB) ile sentezlenmesi ve analizine, ayrıca potansiyel uygulamalarına yer verilmiştir. Borofenin kalınlık kontrollü olarak homojen büyütülmesi, 2 boyutlu malzeme tabanlı yüksek performanslı cihaz üretiminde kritik öneme sahiptir. Borofen, Grafene benzer özelliklere sahip olup kristal yapısı, yüksek çekme gücü ve elektrik iletkenliği gibi özellikleri nedeniyle, sensör uygulamaları, foto detektörler, gaz sensörleri, 2 boyutlu enerji depolama uygulamaları gibi birçok alanda cazip bir malzeme haline gelmiştir. Sonuçlar, borofen tabanlı cihazların potansiyelinin yüksek olduğunu göstermektedir. Bu potansiyel, yüksek kristalli ve katmanlı iki boyutlu düzenleme gibi benzersiz yapısal özellikler nedeniyle elde edilmiştir. Metal alt taşlarında borofenin büyütülmesi, kolay bir şekilde sentezlenirken, yüksek kaliteli analiz imkânı ve performanslı cihazlar için kritik olan Si/SiO_2 alt taşlarında büyütülmesi, katalizör etkisi azaldığı için daha zor olur. Bu zorluk, KBB parametreleri olan basınç, reaksiyon sıcaklığı, gaz akış oranı, kimyasal toz miktarları gibi birçok KBB parametresi optimize edilerek borofenin Si/SiO_2 alt taşı üzerine başarılı şekilde büyütülmesiyle aşılmıştır.

Anahtar kelimeler: Borofen, KBB, Si/SiO_2

Analysis and Direct Synthesis of Borophene on Si/SiO_2 Substrate using CVD Method

Abstract: This study presents the synthesis and analysis of borophene by chemical vapor deposition (CVD) on Si/SiO_2 substrate, as well as its potential applications. The controlled growth of borophene with homogeneous thickness is crucial for the production of high-performance devices based on two-dimensional materials. Borophene, with its graphene-like properties, including crystalline structure, high tensile strength, and electrical conductivity, is a promising material for various applications, such as sensors, photodetectors, gas sensors, and 2D energy storage devices. The results demonstrate the potential of borophene for the development of essential devices. This potential is attributed to its unique structural features, including high crystallinity and layered two-dimensional arrangement. While borophene can be easily synthesized on metal substrates, its growth on Si/SiO_2 substrate is more challenging due to the reduced catalyst effect. However, this challenge was overcome by optimizing the CVD parameters, including pressure, reaction temperature, gas flow rate, and chemical powder concentration, resulting in successful growth of borophene on Si/SiO_2 substrate.

Keywords: Borophene, CVD, Si/SiO_2

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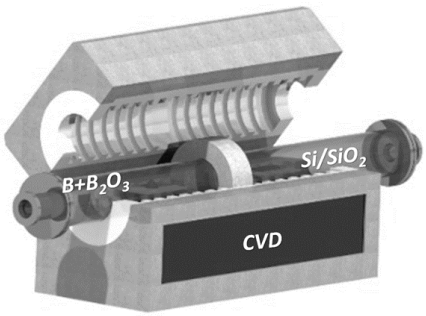
1. Giriş

Grafenin keşfiyle iki boyutlu malzemelere olan ilgi artarak devam etmektedir (Novoselov ve ark., 2005a; Geim ve Novoselov, 2007). İki boyutlu malzemelerin yapısal özellikleri bakımından ele alındığında kristal yapı özellikleri, elektriksel özellikleri, manyetik özellikleri, yüzey özellikleri nedeniyle birçok araştırmaya konu olmuştur. Bu araştırma konularıyla ilgili akademik çalışmalar artarak devam etmektedir (Novoselov ve ark., 2005b). Grafene benzer özellikleriyle ilgi çeken diğer bir malzeme ise borofendir (Hou ve ark., 2020). Borofen içyapısal özellikleri ve 30 dan fazla kristal örgü çeşidi olması nedeniyle araştırma konularında önemli merak konusu olmuştur (Rahman ve ark., 2023). Bu gizemli malzemenin bazı özellikleri 2 boyuta düştüğünde değişmesi, birçok uygulamada cihaz üretimi olarak karşımıza çıkmaktadır (Somesh ve ark., 2024). İki boyutlu malzemelerin üretiminde kimyasal aşındırma, mekanik eksfoliasyon, fiziksel buhar biriktirme (PVD), kimyasal buhar biriktirme (KBB) birçok yöntem bulunmaktadır. Bu yöntemlerin içinde KBB kullanım kolaylığı ve birçok parametrelerin olması bakımından çok kullanışlı bir yöntemdir (Bay ve ark., 2019). Bu çalışmada, özellikle metal alt taşların katalizör etkisiyle üzerinde homojen ve tam kaplama olacak şekilde borofen büyütülmesi başarılmıştır ancak borofenin, kalınlık kontrolü dâhil 300

nm silikon dioksit kaplı silikon alt taş (Si/SiO_2) üzerinde homojen tam kaplama ve büyütmesi araştırma ve geliştirme aşamasındadır (Yu ve ark., 2022). Si/SiO_2 alt taşı cihaz tasarımında ve analiz işlemlerinde en çok kullanılan alt taşlardan biridir (Kobayashi ve ark., 2008). Örneğin bakır üzerinde büyütülen Si/SiO_2 AFM (Atomik Kuvvet Mikroskobu) ölçümü alabilmek için Si/SiO_2 alt taşı üzerine transfer etmek gerekir aynı şekilde optik mikroskop ölçümü SEM (Taramalı Elektron Mikroskobu) ölçümü gibi önemli analizlerde Si/SiO_2 alt taşı kullanılmasının avantajı vardır (Chen ve ark., 2017). Bu çalışmada transfer işleminde oluşan kayıplara engel olacak yöntem geliştirilmiştir. Yapılan birçok deneyin ardından gaz akış hızı, sıcaklık, sıcaklık yükseliş süresi gibi birçok KBB parametrenin optimizasyonu sonucunda bir KBB reçetesi geliştirilmiştir ve borofenin KBB yöntemiyle Si/SiO_2 alt taşı üzerine direkt büyütülmesi başarılı şekilde gerçekleşmiştir. Bu çalışmada, borofenin Si/SiO_2 üzerine büyütme ile ilgili geliştirilen yöntem ve analizler iki boyutlu malzeme tabanlı yüksek teknolojik cihazların üretimini kolaylaştırdığı ve performansını arttırabileceği için ümit vadetmektedir. Bu çalışmanın literature katkısı, yüksek performanslı cihaz üretimi için önem arzeden borofen yapılarının transfer işlemine gerek kalmadan direkt olarak Si/SiO_2 alttaşı üzerinde büyütülmesi ve analizidir.

2. Materyal ve Yöntem

Borofen sentezi için yapılan birçok deneyin ardından oluşan KBB reçetesi, KBB parametrelerinin optimizasyonu sonucunda oluşmuştur. KBB parametreleri, örneğin, gaz çeşidinden hidrojen (H_2) 0-100 sccm, Nitrojen (N_2) 0-100 sccm, argon (Ar) 0-100 sccm arasındadır. Sıcaklık iki farklı alanda olmak üzere 0-1000 °C' arasındadır. İki farklı sıcaklık alanı arasındaki sıcaklık farkı ilave izolatör parçaların sayesinde 350 °C kadar ayarlanabilmektedir. Vakum cihazı ve kontrolör sayesinde 2 Torr – 750 Torr arasında basınç ayarlanabilmektedir. Normal basınçta 1000 °C üzerinde olan erime sıcaklığını basıncı düşürerek erime sıcaklığını da 1000 °C altına çekerek aynı malzemenin buharlaşması kontrol edilebilmektedir. Substrate çeşidi olarak cam, kuvars, Si/SiO_2, bakır (Cu), tungsten (W), molibden (Mo) alt taşları gibi birçok substrate bulunmaktadır (Xie ve ark., 2020). Metal alt taşları üzerinde büyütülen borofenin analizi ve yüksek performanslı aygıt üretimi için Si/SiO_2 alt taşı üzerine transfer edilmesi gerekmektedir. Transfer işleminde uygulanan işlemler nedeniyle iki boyutlu üretimin zarar görmesine yüzey çatlakların ve deformasyonun oluşmasına alt taşla borofen arasındaki bağların kırılmasına, kayıpların artmasına ve dolayısıyla analiz ve yüksek performanslı cihaz üretimine olumsuz etkilemektedir. Bu sorunu bertaraf etmek için, Si/SiO_2 alt taşı üzerine direkt olarak KBB büyütülmesi çok önemli bir ihtiyaçtır. Çünkü kaliteli analizler yapılabilmesi ve iki boyutlu - yüksek performanslı cihaz fabrikasyonu için homojen temiz büyütülmüş borofen gerekiyor. Si/SiO_2 alt taşın üzerinde yaklaşık 300nm Si/SiO_2 olan alt kısmında silisyum olan bir alt taştır. Si/SiO_2 alt taşın birçok avantajı vardır, bunların başında, kaliteli analiz sonuçları gelir, örneğin optik mikroskopta analiz yaparken, yüzey görüntüyü görmemiz için uyumludur. Başka bir örnek AFM ölçümüdür. Piezoelektrik malzemeyle belirli bir potansiyel farkla yüzeyle mesafe kullanarak ölçüm yapan AFM cihazı, pürüzlülüğü ölçerken alt taşın daha az pürüzlü olmasıyla, 2 boyutlu yapının yüzeyinden pürüzlülük ölçümü alındığında daha az pürüzlülük değeri verecektir. Diğer bir örnek ise SEM cihazında yüzeyde metal alt taş üzerinde büyütmelere göre daha az elektrik şarlanması yapar. Si/SiO_2 üzerinde büyütülen örneklerin hem düz zeminde olması hem de yalıtkan zeminde olması avantajdır ve yüksek çözünürlüklü SEM görüntülerin kalitesine olumlu etki etmektedir. I-V ölçümünde alt taşın metal olmadığı için zeminin IV grafiğine etkisi minimumdur. EDX (Enerji dağıtıcı X-ışını spektroskopisi) ve XRD (X-ray spektroskopisi) de aynı durum söz konusudur. Si/SiO_2 üzerinde homojen şekilde borofen üretimin yapılamamasının nedeni, metaldeki katalizör etkisinin olmayışıdır. Metal alt taşlar metal özelliklerinden dolayı katalizör etkisi yaparak bor atomlarının birbiriyle ve metal alt taş yüzeyi ile bağ kurması için daha uygun hale getirir ve borofen yapılarının homojen büyümesine olumlu etki eder. Katalizör etkisinden yola çıkarak, borofenin geçiş metalleriyle etkileşimden dolayı ortaya yeni malzemeler çıkıyor ve metal borürler ismiyle tanımlanıyor (Zha ve ark., 2019). Borofen büyütmede her hangi bir geçiş metalini KBB yönteminde alt taş olarak kullanılması durumunda Si/SiO_2 alt taş olduğu duruma göre homojen ve tam kaplama olarak büyüdüğü gözlemlenecektir. Bu çalışmada, metal alt taşı üzerinde tam kaplama borofen büyütme, Si/SiO_2 alt taşı üzerinde kaliteli analiz sonuçları ve yüksek performanslı cihaz üretimi imkânını aynı anda sağlayacak şekilde KBB parametreleri geliştirilmiştir. Borofenin Si/SiO_2 üzerinde direkt olarak homojen, tam kaplama, kalınlık kontrollü olacak şekilde büyütülmesi başarıyla gerçekleşmiş, üretilen borofen yapılarını olumsuz etkileyen transfer işlemine gerek kalmamıştır. Borofenin Si/SiO_2 alt taşı üzerinde büyütürken, reaksiyon sıcaklığı 1000 °C ve reaksiyon süresi 20 dakika olarak optimize edilmiştir. Vakum şartlarında gerçekleşen KBB reaksiyonları için 100 sccm N_2 ve 20 sccm H_2 gazı KBB sistemine verilmiştir. Boron (B) ve Diboron trioksit (B_2O_3) kimyasal tozların oranı 1:1 olarak belirlenerek toplamda 50 mg kimyasal karışım kuvars plakaya eklenmiştir. Kimyasal tozlar ile Si/SiO_2 alt taşı arasında 30 cm mesafe bırakılarak deney seti hazırlanmıştır (Şekil 1). Birçok deneyin ardından elde edilen KBB reçetesi, tekraren yapılan deneyleriyle aynı parametreler ile borofenin Si/SiO_2 alttaşı üzerinde büyütülmesi test edilmiş, reçetenin başarılı olduğu tespit edilmiştir.



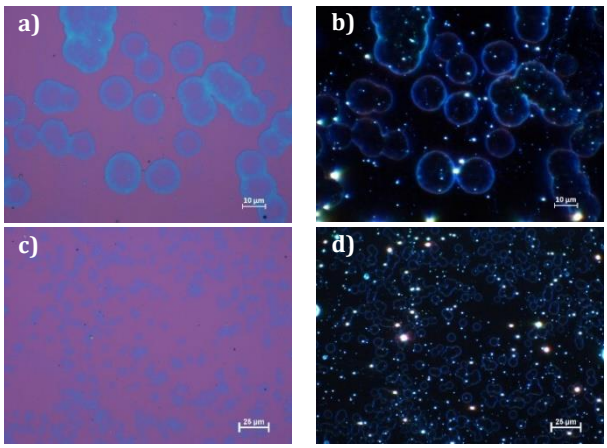
Şekil 1. Kimyasal buhar biriktirme (KBB) sistemi.

Borofenin KBB ile Si/SiO_2 alt taşı üzerinde büyütülmesinden sonra, analiz aşaması başlar. İlk olarak optik mikroskopta yüzey formasyonu ve kaplama oranı incelenen borofen yapıları daha sonrasında XRD kristal yapısı incelemek için analiz yapılır. Yüksek çözünürlüklü SEM ile borofen yapılarının yüzey morfolojisi incelenir. EDX kullanılarak Si/SiO_2 alt taşı ve borofen yapılarının yüzdelik oranda kimyasal ve element olarak dağılımı tespit edilir. Raman spektroskopisi sayesinde borofen yapılarının kendi aralarında ve Si/SiO_2 alt taşı arasındaki bağların moleküler titreşimleri analiz edilir. AFM atomik kalınlıklarda üretilen borofen yapılarının topograf analizi gerçekleştirilir. Son olarak üzerine metal kontaklar atılmış borofen yapılarının akım-gerilim (I-V) ölçümü yapılarak incelenir.

3. Bulgular

3.1. Optik Mikroskobu Ölçümü

Borofenin yapılarının optik mikroskobu ölçümleri, homojen kaplama oranı ve yüzey formasyonu hakkında bilgi edinmek için alınmıştır (Şekil 2). İlk olarak 10 µm bar ölçekli bright ve dark field modunda ölçümler alınmış yüzeyin detaylarını daha rahat gözlenmesi sağlanmıştır (Şekil 2a ve 2b). Daha sonra 25 µm barlı ölçümler alınmıştır bu ölçümler mikroskobun 50x merceğinde alınmıştır (Şekil 2c ve 2d). Bu sayede borofenin Si/SiO_2 alt taşı üzerine direk büyütülmesinde homojen kaplamanın olduğu gözlenmiştir.

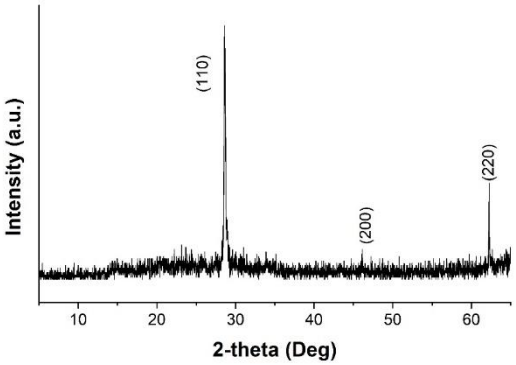


Şekil 2. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin optik mikroskobu ölçümleri a) bright field 100x, b) dark field 100x, c) bright field 50x, d) dark field 50x.

3.2. XRD Ölçümü

Borofenin X-ray spektroskopisi ölçümü 0°-90° arasında alınmış olup her dakikada 2° olacak şekilde ilerleme sağlanmıştır (Şekil 3). Yaklaşık 45 dakika süren ölçümün sonucunda alınan tepe değerleri; 28° (110), 48° (200), 63° (220) derecelere denk gelmiştir ve sonuçlar literatür ile uyumludur (Chinnalagu ve ark., 2023). En uzun tepe değeri olan 28° de (110) tepe değeri verilerini Scherrer denklemini (1) uyguladığımızda parçacık size değeri yaklaşık olarak 17 nm olarak hesaplanmıştır (Alemán-Vázquez ve ark., 2005). Scherrer denkleminde D kristal grain büyüklüğünü (nm), K boyutsuz sabit sayıyı (0.9), λ (nm) X-ray dalga boyunu, β (rad) yarı maksimumdaki tam genişlik değerini, θ (rad) Bragg açısını niteler (eşitlik 1).

$$D = \frac{K\lambda}{\beta cos\theta} \qquad (1)$$

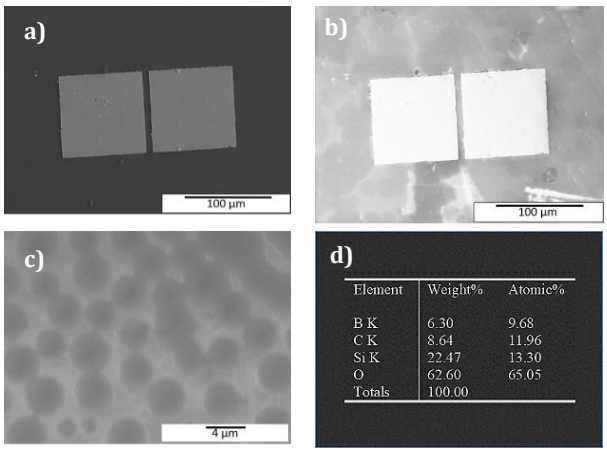


Şekil 3. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin XRD ölçümü.

3.3. Yüksek Çözünürlüklü Taramalı Elektron SEM & EDX Ölçümleri

Borofenin yüksek çözünürlüklü (SEM & enerji dağıtıcı x-ışını spektroskopisi (EDX) ölçümleri borofen yapıları, metal kontak yüzeyleri daha ayrıntılı inceleme imkânı sunmuştur. Ölçüm alınırken EHT değeri 20 KV, magnifikasyon değeri 1000x ve 5000x, working distance (WD) değeri 8 mm olarak ayarlanmıştır. SEM ölçümlerinde görüntülerin detaylarını incelemek için farklı modlarda görüntü ölçümü alınmıştır. Bu görüntüleme modları inlens ve secondary electron modu olarak tanımlanır. İki modun farklarını aynı şekil üzerinden alınmış iki farklı moddaki görüntü ölçümünden bakarak incelenebilir (Şekil 4a ve 4b). Şekil 4b bakıldığında inlens modunda en üstteki metal kontak yüzeyinin detaylı gözüktüğü ve secondary electron modda ise Si/SiO_2 alt taşı ile metal kontak arasında bulunan borofen yapılarının detaylarını gözüktüğü tespit edilmiştir. Borofenin Si/SiO_2 üzerine kapladıktan sonra, fotolitografi işlemi yapıldı ve daha sonrasında metal evaporatör cihazıyla Au/Ti metal kontaklar atıldı. Uzun süren bu işlemin ardından yüzeye nasıl kontak yaptığını gözlemlemek için SEM görüntüsünü alındı. Şekil 4c ve 4d ise tek katmanlı borofen yapılarını SEM ölçümü vasıtasıyla inceleme imkânı sunmaktadır. Ek olarak aynı

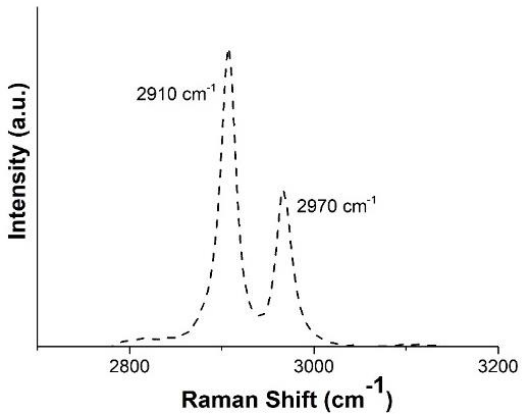
alandan alınan EDX ölçümünden alınan sonuçlara göre; ağırlık olarak borofen (B) % 6,30, karbon (C) % 8,64, silikon (Si) % 22,47, oksijen % (O) 62,60. Atomik olarak borofen (B) % 9,68, karbon (C) % 11,96, silikon (Si) % 13,30, oksijen (O) % 65,05 olarak rapor edilmiştir. Sem ölçümlerine bakıldığında, borofenin benzer formda ve homojen şekilde büyütüldüğü ispatlanmıştır.



Şekil 4. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin SEM ölçümü: a) Au/Ti metal kontak inlens mod, b) Au/Ti metal kontak sekonder elektroıı mod, c) tek katmanlı borofen yapıları, d) tek katmanlı borofen yapıların EDX ölçümü.

3.4. Raman spektroskopisi Ölçümü

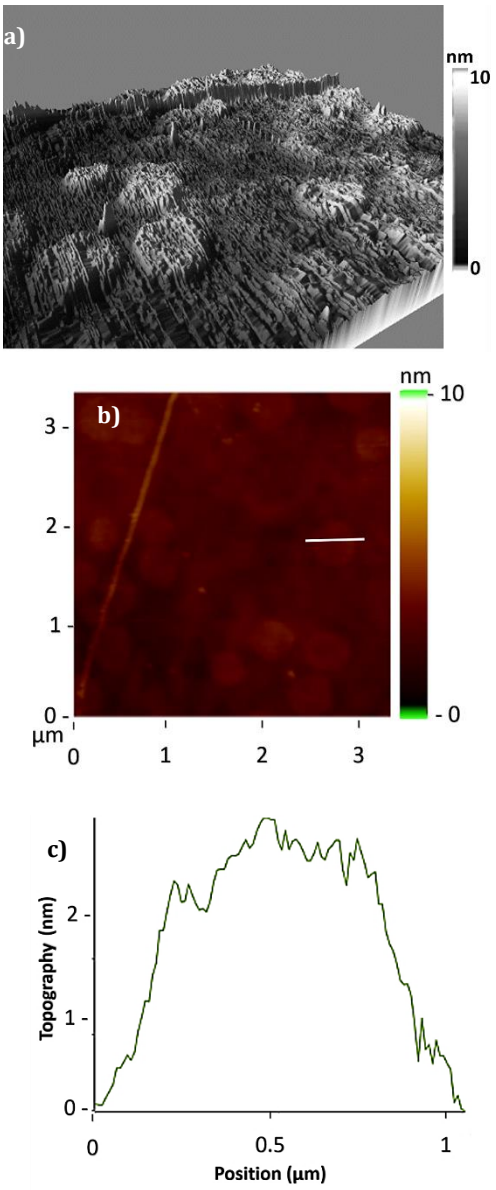
Si/SiO_2 üzerine büyütülmüş borofenin sahip olduğu bağların titreşimleri hakkında veri alabilmek için Raman spektroskopisi ölçümü yapıldı. Sonuçlara bakıldığında borofene has 2910 cm^{-1} ve 2970 cm^{-1} de oluşan tepe değerleri bulunmaktadır (Şekil 5). Borofeni niteleyen bu iki tepe değeri D+G overtone tepe değerine denk gelmektedir (Childres ve ark., 2013). Bu tepe değerleri, tek katma ve az katmanlı (2-3 layer) borofen yapılarına has değerlerdir.



Şekil 5. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin Raman spektroskopi ölçümü.

3.5. AFM Ölçümü

Si/SiO_2 üzerine büyütülmüş borofenin AFM ölçümleri atomik seviyede üretim yapıldığını göstermek amacıyla topograf analizi gerçekleştirildi (Şekil 6). Piezoelektrik malzemelerin kullanıldığı AFM cihazında yüzeye dokunmadan yaklaşık 2 Volt değerinde bir potansiyel fark ayarlanarak yüzeye dokunmadan yani dinamik modda ölçüm alınmaktadır. Şekil 6a tomografik ölçümün 3 boyutlu olarak simülasyonu görülmektedir. Yüzeye dikkatli bakıldığında çalışmanın önceki analiz sonuçlarıyla uyumlu ve benzer disk şekilli yapıların oluştuğu gözlenebilir. Şekil 6b de ise topografı ölçümü görülmektedir yine benzer disk görünümlü borofen yapıları tespit edilmiştir. İçlerinden örnek borofen yapısı seçilerek üzerindeki çizgi ile profil kalınlığı yaklaşık 2,5 nm olarak tespit edilmiştir (Şekil 6c).



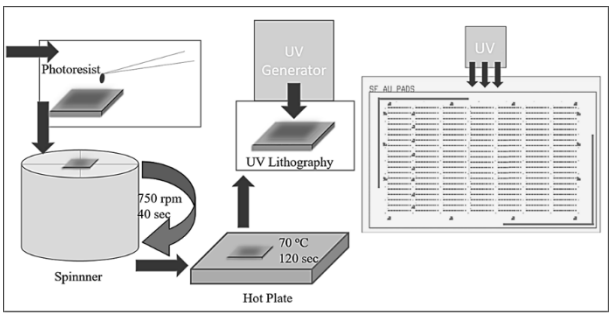
Şekil 6. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin AFM ölçümü: a) 3 boyutlu gösterim, b) topoğraf ölçümü, c) kalınlık profili.

XRD ve AFM sonuçları arasında direkt olarak bağlantı bulunmamakla birlikte, XRD ölçümünden hesaplanan parçacık boyutu; yapının lateral büyüyen kristal örgünün boyutunun hesaplandığı bir değerdir. AFM ölçümünde ise

kalınlık ölçümü yapılmaktadır. İki veri arasında değerlendirme yapılacak olursa, lateral olarak kristal örgünün daha büyük değerde olması, tek tip yönlenme olması daha kalite kristal yapının olduğunu gösterirken, AFM ölçümünde pürüzlülük değeri ve kalınlık değerinin küçük olması kaliteli homojen bir büyütme olduğunu gösterir.

3.6. Fotolitografi & Metal Kontak Prosesleri

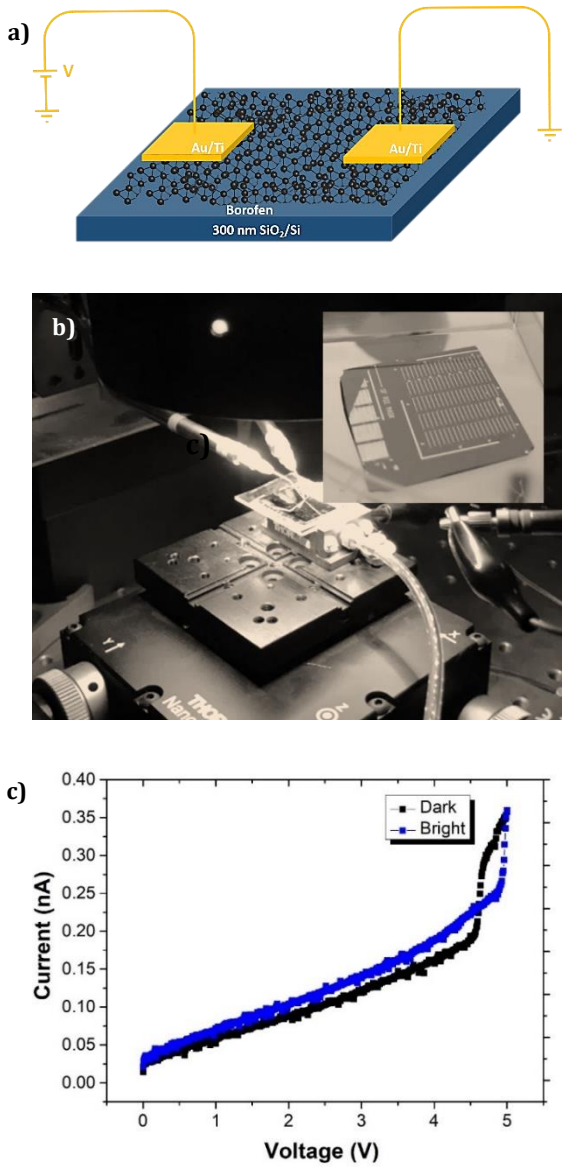
Fotolitografi Si/SiO_2 alt taşı üzerinde büyütülen borofen yapıları üzerine metal kontak üretimi için kullanılan önemli ve birçok detaylı işlemi olan metottur, borofen yapılarının, bir maskenin yardımıyla, ışığa duyarlı bir direnç üzerine görüntülenmesiyle başlar (Hubenthal, 2011). İşlemlerin dikkatlice yapılması gerekir, zira hata yapıldığında uzun süren bu zorlu süreç baştan başlamaktadır. Fotolitografi ile metal kontak üretimi, transfer işlemi olmadığı için Si/SiO_2 üzerinde direkt büyütülmüş borofen yapıların daha sağlam olması, geniş alanda büyütülmüş olması ve homojen olması nedeniyle daha kaliteli sağlam kontak atma imkânı sağlıyor. Çünkü metal kontak alınacak alanda tamamına yakını borofenle kaplanmıştır her hangi bir yırtılma çekme deformasyon söz konusu değildir. Direkt büyütmenin en büyük avantajı fotolitografi işlemine sağlam zemin oluşturulmasıdır. Fotolitografi işlemi yapıldığında kolayca koparak gitmez. Fotolitografiye hazırlık işlemleri homojen kaplı borofen yapılarının üzerine fotoresist damlatılarak yüzeyde bir kaplama oluşmasıyla başlar, daha sonra spinner ile 750 rpm ve 40 saniye olarak döndürülür. Bu işlemin amacı yüzeye homojen yayılma ve kururken aynı kalınlık elde etmektir. 70 °C de 120 sn sıcak plaka cihazında bekletilir, kurutma işlemi gerçekleşir. UV cihazı ile maskenin ışığı geçirgen kısımlarından geçen UV ışınları fotoresist kaplı alanları kaldırır ışığın geçmediği alanlarda fotoresist kaplı şekilde kalır. Daha sonra metal evaporatör cihazı kullanılarak bu boşluklara Au/Ti kaplanır. Kaplama işlemi 10 nm titanyum (Ti) 90 nm altın (Au) kaplanır. Tüm yüzeyin bu iki metal ile kaplanmasının ardından, asetonda 70 °C de bekletilerek cımbız yardımıyla hafif titrasyon yapılır ve fotoresist olan kısımların altın ve titanyumla birlikte kalkması sağlanır ve yüzeyde borofen üzerinde sadece metal kontaklar kalır. SEM ölçümlerinde görüldüğü üzere metal kontaklar homojen pürüzsüz ve kaliteli şekilde kaplanmıştır. Bu kaplamaların borofen yapıları üzerinde olması alınacak ölçümler ve üretilecek cihazlar için önem arz etmektedir. Fotolitografi işlemlerinin kaliteli şekilde tamamlanarak metal kaplama işleminin sağlam olabilmesini için borofenin Si/SiO_2 üzerine direkt sentezlenmesi kritik öneme sahiptir.



Şekil 7. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin üzerine metal kontak yapılarının fabrikasyonunda kullanılan fotolitografi işlemleri.

3.7. Akım-Gerilim (I-V) Ölçümü

Si/SiO_2 alt taşı üzerine büyütülmüş borofenin metal kontaklarını kullanarak alınmış I-V ölçümü görülmektedir (Şekil 8). Şekil 8a metal kontak kaplanmış borofen yapılarının üç boyutlu gösterimi yapılmıştır. Şekil 8b de I-V ölçümü için kullanılan prop istasyonu görülmektedir. Prop istasyonunun metal iğneleri kullanılarak borofen yapılarının üzerinde bulunan metal kontaklara temas ederek, kapalı devre kurulmuş olur. Bu devre üzerinde I-V ölçümü alınmıştır. Alınan ölçümlerde bright ve dark ortamda alınarak farkına bakılmıştır (Sahoo ve ark., 2023). 0-5 volt aralığında uygulanan gerilimin sonucunda akımın maksimum 0,35 nA olarak ölçülmüştür (Şekil 8c). Literatürde yayınlanan çalışmalardan biri olan borofenin zararlı gaz detektörü uygulamasındaki I-V sonuçlarıyla uyumlu olduğu tespit edilmiştir (Tian ve ark., 2021). Altın kontakların borofen yapılarının üzerinde fabrike edilmesinden sonra alınan I-V ölçümü karanlık ve aydınlık ortamda voltaj değeri ise 0-5 V aralığında alınmıştır. Gaz sensörü uygulamasında potansiyeli olan bu testin Tian ve arkadaşlarının çalışmasında 0-1 volt aralığında alındığı görülmektedir. Bizim çalışmamızda ise yaklaşık 4 volt değerine kadar lineer bir artış görülmektedir. 4.5 V değerinden sonra oluşan değişim, borofen tabanlı cihazın ışığa karşı hassasiyeti nedeniyle oluşmuştur. Si/SiO_2 alt taşı üzerine büyütülmüş borofen araştırması ilerleyen aşamalarda, özellikle foto detektörü ve gaz detektörü gibi cihaz uygulaması olarak potansiyeli vardır.



Şekil 8. Si/SiO_2 alt taşı üzerinde büyütülmüş borofenin I-V ölçümü a) 3 boyutlu gösterim, b) prop istasyonu, c) IV grafiği.

4. Tartışma

Elde edilen bulgular ışığında, borofenin Si/SiO_2 üzerine büyütülme ihtiyacı tespit edilmiş homojen ve kontrollü şekilde büyütme gerçekleşmiştir. Daha sonra üretilen borofen yapılarının AFM, Raman, EDX, SEM, XRD gibi önemli mikro analizleri yapılarak fiziksel ve yapısal özellikleri incelenmiştir. I-V ölçümüyle akım gerilim ölçümü incelenmiştir. Fotolitografi ve aygıt fabrikasyonu için çok önemli bir sorun olan transfer işlemine gerek duymadan direk büyütme gerçekleşmiştir. Transfer işlemlerinin dezavantajlarından; yüzey kırılmaları malzeme, deformasyonu, kaplanan yüzeyin büyük bir kısmının transfer edilen yüze transfer edilmemesi gibi önemli problemlerin olumsuz etkileri ve riskler bertaraf edilmiştir. Borofenin Si/SiO_2 üzerine KBB yöntemiyle direkt büyütülmesi bir yandan zamandan ve kimyasal işlemlerden ve proje bütçesinden tasarruf sağlarken, öte yandan kaliteli analiz imkânı sağlamaktadır ve 2 boyutlu malzemelerden üretilecek yüksek performanslı aygıtları için zemin oluşturmaktadır.

5. Sonuç

Bu çalışma borofenin Si/SiO_2 alt taşı üzerinde KBB yöntemiyle büyütülmesi ve analizini göstermektedir. Optik mikroskobu, Raman spektroskopisi, SEM, EDX, XRD, AFM, I-V analizleri sonucunda borofenin yapısıyla alakalı bilgiler rapor edilmiştir. Transfer işlemine gerek duymadan büyütülmenin yapılabilmesi 2 boyutlu malzeme tabanlı, yüksek performanslı cihazların üretiminde önem arz etmektedir. Borofenin direkt olarak Si/SiO_2 alt taşı üzerinde büyültmesi bu alandaki araştırma ve geliştirme çalışmalarına ümit verici değerli bilgiler sağlamıştır. Yakın gelecekte, iki boyutlu malzeme tabanlı cihazların üretiminde sağlanan bu kolaylık sayesinde, daha yüksek performans gösteren, uzun ömürlü, sağlam aygıtlar üretilebilir.

Katkı Oranı Beyanı

Yazarın katkı yüzdeleri aşağıda verilmiştir. Yazar makaleyi incelemiş ve onaylamıştır.

	M.B.
K	100
T	100
Y	100
VTI	100
VAY	100
KT	100
YZ	100
KI	100
GR	100
PY	100
FA	100

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedir.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

Destek ve Teşekkür Beyanı

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Research Article
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INVESTIGATION OF THE EFFECTS OF EXTRACTION POLARITY CHANGE ON THE BIOACTIVITY OF *Eruca Vesicaria*

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Abstract: *Eruca vesicaria* (arugula) plant is frequently used today as a daily food source that contains a rich variety of minerals and vitamins, especially vitamin C. It also contains a high percentage of phenolic compounds which are structures that plants develop to protect themselves from harmful organisms. Phenolic compounds found in plants are obtained by different extraction methods and have a high antioxidant effect. In this study, we report, anticancer activity extract from *Eruca vesicaria* against human prostate cancer cells (PC-3) in vitro. The phenolic substances contained in the plant were obtained in different concentrations by the extraction technique based on the polarity difference. HPLC and total phenol content were determined to perform extraction content analysis. According to in vitro MTT cell proliferation assay, it acted at high concentrations, regardless of polarity differences. The highest cytotoxic effect was observed in extract extracted with 50% ethanol concentration. It has been observed that it has an anticancer effect compared to the determination of total phenol content. Also, because of 24-hour MIC analysis, it shows antibacterial properties according to agent concentration. As a result of this study, it adds many new information to the literature, but also provides guidance for future research.

Keywords: *Eruca vesicaria*, Anticancer, Antibacterial, Phenolic contents, HPLC

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1. Introduction

Food consumption plays an important role in modulating certain degenerative processes that affect an organism's quality of life. The strongest evidence that vegetables and fruits are associated with a potential reduction in cancer risk comes from epidemiological studies (Gasper et al., 2007). Arugula species (*Eruca vesicaria*), which are among the vegetables, contain a range of phytochemicals that support health, including carotenoids, vitamin C, fibers and polyphenols (Bell and Wagstaff, 2019). *Eruca vesicaria* is thought to be an excellent source of antioxidants, such as phenolic compounds (Boyd et al., 2011). *Eruca vesicaria*, which grows in aquatic environments, is a plant that regulates its bioactive chemical content according to the amount of water in growing conditions (Bianco and Boari, 1996). *Eruca vesicaria* is a plant species rich in various minerals and vitamins, especially vitamin C. At the same time, this biochemical content gives the plant its own bitter taste and aroma (Bell and Wagstaff, 2019). The main bioactive chemical ingredients of the plant are phenolic compounds in general (Gillian, 2009). Phenolic compounds are an important group of bioactive chemicals that determine the taste, aroma and color of plants. In general, these substances are compounds that contain one or more hydroxyl groups in their aromatic ring. Structures with a single hydroxyl group are called phenols, and all phenolic compounds are thought to derive from this group. Nowadays, more than five thousand phenolic substances have been identified in plants (Bennett et al., 2006).

Developing technology and changing living conditions cause various diseases in today's world. The most important of these diseases is cancer. The effect of free radicals on the formation of cancer is among the topics frequently explored in scientific studies (Peroni et al., 2019). Antioxidant substances are used to prevent the formation of these free radicals or reduce the existing ones. In this context, plant-derived antioxidants and phenolic compounds serve as free radical scavengers with high reduction capacities (Jin et al., 2009, Allen and Tresini, 2000).

Various extraction methods are used to obtain these antioxidants provided from plants (Kim and Ishii, 2006). Productivity has also increased with the use of chemicals. However, research in the literature shows that comments are made on the results made with a single solvent. It is known that changing the polarity of the solvent will change the type and amount of the dissolved substance (Lamy et al., 2008; Bell et al., 2015).

The extraction of *eruca vesicaria* plant was done with 3 different polarity solvent groups. The phenolic change in the content of the obtained herbal extracts was determined by the ultra-pressure liquid chromatography

method (UHPLC) and spectroscopic analysis method. The content of matter was calculated by UHPLC method, and the total amount of phenol was determined by spectroscopic method. The effect of phenolic substance quantity changes on gram-positive and gram-negative bacteria was examined. Disc diffusion sensitivity test and microplate test were performed, where the presence of antibacterial property and how effective it would be if it existed were calculated. Finally, the anticancer effect on prostate cancer was measured using the MTT test.

2. Materials and Methods

2.1. Reagent

Dulbecco's modified Eagle's minimal essential medium-high glucose (DMEM), fetal bovine serum (FBS), MTT dye (thiazolyl blue tetrazolium bromide), ethanol (%99), acetic acid and acetonitrile were supplied from Sigma-Aldrich (St Louis, MO, USA). Antibiotic/antimycotic solution was purchased from Biological Industries (Cromwell, CT, USA). Dimethyl sulfoxide (DMSO), sodium carbonate and Folin-Ciocalteu reagent were obtained from Merck (Darmstadt, Germany).

2.2. Extraction of Plant Materials

The *Eruca vesicaria* plant was taken and washed, the remains of agricultural medicine and soil were removed and dried at room temperature. *Eruca vesicaria* leaves were ground in a bench top mill. Ethanol was prepared in three different concentrations: 10%, 50% and 90%, then these were mixed with freshly ground *eruca vesicaria* in a ratio of 1:10 under magnetic stirring at room temperature for 24 hours. At the end of the required extraction time, the liquid extract was filtered with vacuum pump, and then ethanol content was removed by using rotary evaporator under vacuum at 45°C. The supernatant of aqueous extract was subjected to freeze-dried.

2.3. HPLC Analysis

High pressure liquid chromatography (HPLC) analysis was performed with a Thermo Scientific Ultimate 3000 HPLC. A reversed-phase column, ODS-2 HYPERSIL RP 18 with a 3-µm particle size (ThermoFisher Scientific, USA), was used at the flow rate of 1 mL min-1. Mobile phase gradient was performed by varying the proportion of solvent A (2.5% acetic acid) to solvent (100% acetonitrile) as follows: initial 1% B; linear gradient to 40% B in 40 minute. The samples were prepared at concentration of 50 mg/ml in 100% acetonitrile and injected sample volume was 20 µl. All solutions were filtered prior to injection through 0.20 µm membrane filters (Millipore, Bedford, MA, USA). The column temperature was at 25°C. The measurement was held at 254 nm.

2.4. Determination of Phenolic Content

Total phenolic content of *Eruca vesicaria* extract was determined by Folin-ciocalteu method (Slinkard and Singleton 1977). Folin-ciocalteu reagent was prepared by 1:10 dilution of stock solution. Sodium carbonate solution of 7% was prepared in distilled water. Gallic acid was used as standard in the calibration curve. *Eruca vesicaria* extract was dissolved in distilled water. 20 µl of each sample was mixed with 100 µl Folin-ciocalteu reagent and incubated for 2.5 min. Then 80 µl of sodium carbonate solution was added. The mixture was kept in dark for 1 hour. Samples were subjected to photometric measurement at 725 nm. The experiments were conducted in 3 replicates, and results were expressed as mg of gallic acid equivalents (GAE)/gr dry weight extract. The phenolic content was defined as gallic acid equivalents using the following linear equation 1 based on the calibration curve:

$$X = 0.99Y + 9.925 \times 10^{(-3)} \quad (1)$$

R2 = 0.9998, where X is the absorbance and Y is concentration as gallic acid equivalents (µg/g).

2.5. Minimal Inhibitory Concentration Assay

Stock solution was prepared with 100% DMSO at a rate of 1mg/ml from the extracts. Dilution was performed for each sample as shown in Table 1. L.monocytogenes, E. coli and 5% DMSO were used as a control group. Bacteria were subjected to serial dilutions. 96 well plates were used for measurement. At the end of all dilutions, 100 µL was first placed in each well in two sets of our diluted samples, then 100 µL was placed in each well from our diluted bacteria.

Table 1. Dilution rates of *Eruca vesicaria* extracts of 10%, 50% and 90% with medium

Concentration	Media	Agent	Total Volume
0.5 mg/ml	960 µL	240 µL	1200 µL
0.25 mg/ml	500 µL	500 µL	1000 µL
0.125 mg/ml	300 µL	300 µL	600 µL

2.6. Cell Culture

The human prostate cancer cell line PC-3 (ATCC CRL-1453) and human embryonic kidney cell line HEK-293 (ATCC CRL-1573) were used in this study and were maintained in DMEM supplemented with 10% fetal bovine serum and 1% antibiotic/antimycotic solution. Then, cells were maintained at 37 °C and 5% CO_2 in an incubator (Nuve EC 160). Cells were subculture every 48 hours.

2.7. Cytotoxic Activity Determination by MTT

The MTT cell proliferation assay was performed to observe the viability of PC-3 cells treated with *Eruca vesicaria* extracts (Eroglu et al., 2020). Cytotoxicity of *eruca vesicaria* extract was evaluated by the MTT (tetrazolium (3-{4,5-dimethylthiazol-2-yl}-2,5-diphenyl tetrazolium bromide) assay. Extract was dissolved and diluted serially in DMEM with FBS(10%) and filter-sterilized. PC-3 cells and HEK-293 cells were incubated in an incubator at 37°C and 5% CO_2. PC-3 cells and HEK-293 cells were grown in the absence or presence of various concentration of *eruca vesicaria* for 24, 48 and 72 hours. Then the cells were exposed to MTT for 3 h in dark at

37°C. Mitochondrial hydrogenases in the viable cells reduce MTT into formazan crystals which can be dissolved in DMSO. Average absorbance value was measured at differences between 690 nm and 570 nm. Cell viability was calculated by using below formula:

Cell viability:100% × ((Average absorbance value of treated cells)/(Average absorbance value of control cells))

3. Results

3.1. Extraction

Extraction processes were performed under constant stirring and at room temperature for 24 hours (Fig. 1A). Color changes were observed depending on the alcohol concentration as desired (Fig. 1B). The resulting extracts were kept inside the glass tubes at +4°C for at least 24 hours so that the chloroplast and chlorophyll residues inside them would collapse to the bottom. Liquid phases separated from chlorophyll and chloroplasts were transferred into lyophilization bottles (Fig. 1B).

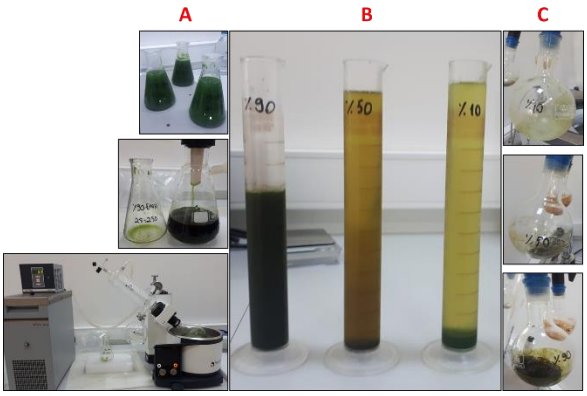

Figure 1. All extraction processes, respectively. A) Sample preparation, filtering and rotary evaporator, B) Color change according to the concentration of ethanol, 90%, 50% and 10% respectively, C) Freeze-dried process (Lyophilization).

Percentage of the extraction yield (25 gram of dry leaves of *eruca vesicaria* was used for extraction) after lyophilization were measured at 18.12% yield for a sample extracted with 10% ethanol, 21.18% yield for a sample extracted with 50% ethanol, and 19.02% yield for a sample extracted with 90% ethanol (Fig. 1C). The structure of the 10% extraction was in the form of powder, while the 90% extraction was obtained in a denser structure. The reason for this is the rate at which phenolic compounds in the content of *eruca vesicaria* are obtained depending on the alcohol concentration. After the extraction processes have been successfully carried out, the characterization phase has been initiated.

3.2. Effect of Extraction Parameters on Total Phenol Content (TPC)

The extracts were analyzed for their total phenolic content by Folin-ciocalteu method. The results can be seen in Table 2 as milligram Gallic acid equivalent per gram dry weight of extract.

Table 2. Total phenol content of *eruca vesicaria* extract prepared at different extraction conditions

Sample	TPC (mg Gallic Acid equivalent/ gr DW)
10% *eruca vesicaria*	63,49
50% *eruca vesicaria*	67,01
90% *eruca vesicaria*	57,66

Total phenol analysis is done to each component and shows how much phenolic compound is in its content. TPC does not give the content of the phenolic compound, it indicates the proportion in which the amount of phenolic is found (Elsadek et al., 2021). Total phenol analysis in three different concentrations was performed for plant extract analysis. It was analyzed in samples that were extracted with the highest 50% and lowest 90% alcohol concentration. This is because phenolic compounds in the *eruca vesicaria* plant were extracted with 10% and 50% ethanol concentrations, while all phenols were obtained and 90% were not sufficient for all phenols. This could be understandable because the polarity of the solvent had a high influence on the solubility of the phenolic compounds. The phenolic content of *eruca vesicaria* consists of substances with polar properties.

3.3. HPLC Analysis of the Extract

The HPLC method is used to analyze which type of phenolic compound is in the content of the resulting component. In our experiment, the aim is that the extraction process performed at different concentrations affects the types of phenolic compounds to be obtained. Our measurements were carried out at a flow rate of 1 mL min-1 with reverse phase column at 254 nm.

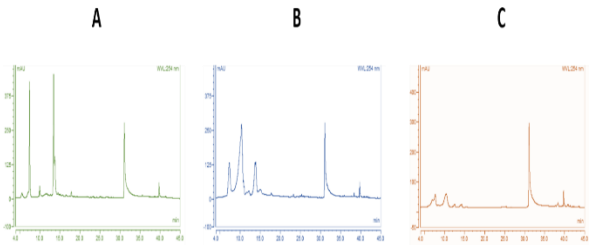

Figure 2. HPLC results of *eruca vesicaria* extracted with 10% (A), 50% (B) and 90% (C) ethanol, respectively. Each of them has been solved in its own solution and subjected to chromatography.

The compositional differences between the extracts which caused the diversity in the total phenol contents were investigated and confirmed by HPLC analysis. HPLC chromatograms showed consistency with total phenolic content results. Although there are proportional differences between the samples, it is observed that the same phenolic compounds are obtained. Phenol intake rates varied depending on alcohol concentration. Similarities have been observed between substances clinging to the column depending on polarity. The first

substance in the samples to come out of the column and reach the detector is the first peak, that is, the drift rate is high, the retention time is short. At the last peak, the drift rate is slow, and the retention time is longer. Due to the polarity difference of the solvent at the extraction stage, Figure 2A and Figure 2C observed field differences in the peaks, although the peaks were read at the same minute. The reason for this is the concentration of alcohol in the extraction stage.

3.4. MIC Experiment

Dilution methods are used to detect MIC values of antimicrobial agents. These methods are reference methods for antimicrobial sensitivity tests. Dilution tests are based on visible reproduction in Microplate wells or on the surface of agar containing dilutions of antimicrobial agent. The lowest concentration of antimicrobial agents, in which the visible reproduction of a microorganism is inhibited, is determined as "Minimal inhibitory concentration (MIC)" (Chiemchaisri et al., 2021; Xia et al., 2021).

The MIC test is a more effective method to determine whether the compound is antibacterial. Bacterial growth is studied depending on the time. Plant extracts prepared in different concentrations have been tested on *L. monocytogenes* and *E. coli* bacteria.

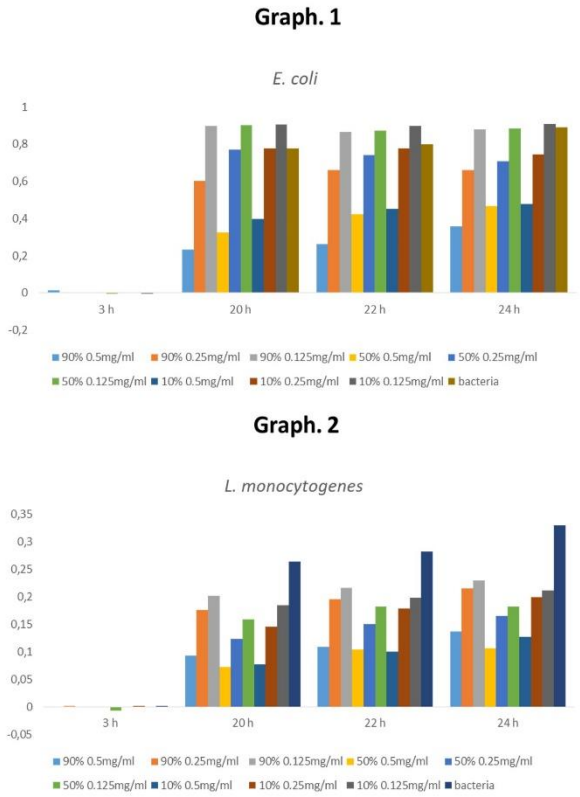

Figure 3. The charts show the results of the MIC analysis method in 3, 20, 22 and 24 hours, respectively. Graph 1.) Measurements taken for *E. coli* according to concentration differences and time changes, Graph 2.) Measurements taken for *L. monocytogenes* according to concentration differences and time changes.

The most bacterial deaths were observed in a sample prepared with 5 mg/ml of 90% for *E. coli* (Fig.3 Graph 1). In 5 mg/ml concentrations of 50% and 10% samples were observed close results at the end of 24 hours. The control group shows the normal growth rate of the bacterium, and our plant extracts of different concentrations have been observed to inhibit growth for the *E. coli*. Samples prepared with 0.125 mg/ml for *E. coli* were not effective, this may be due to the high resistance of the bacterium or low concentration of the agent.

For *L. monocytogenes* (Fig.3 Graph 2), the most bacterial deaths were the sample prepared with 5 mg/ml of 50%. At the end of 24 hours, there was also death at 5 mg/ml concentrations of 90% and 10% samples. Plant extract was more effective in this type of bacteria, while the control group was the normal growth rate of the bacteria, the samples extracted in different concentrations and prepared in different concentrations were all less than the normal growth rate of the bacterium and showed antibacterial effect for the *L. monocytogenes*.

3.5. MTT Cell Proliferation Assay

The MTT viability test was performed to observe how the extractions affected human prostate cancer cells for cytotoxicity analysis. The goal is to test whether the *eruca vesicaria* plant has an anti-carcinogenic effect. For this purpose, PC-3, a prostate cancer cell, and HEK-293, a healthy kidney cell, were used as a control group. In Fig.4, MTT assay was performed with different concentrations of prepared agents of the *eruca vesicaria* plant extracted according to the polarity change.

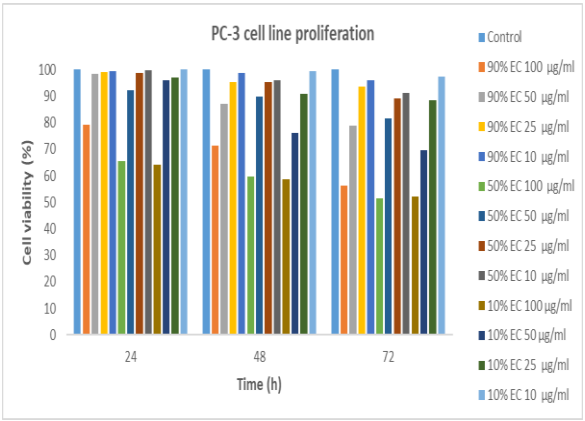

Figure 4. MTT test result on prostate cancer cell line PC3 according to time and concentration change of extracted plant according to time. In figure extraction conditions ethanol concentration of 10%, 50% and 90%, and their different concentration of extract. Human embryonic kidney cell line HEK-293 was used for control group.

Human embryonic kidney cells were used to study the cytotoxicity activity of extraction. The results showed that the agent at each concentration does not kill HEK-293 cells. The bar shown in blue in Figure 4, called control, represents HEK-293 cells. Since no death due to the extract was observed in the experiments performed here, it is shown as a single bar to simplify the graph. In

Figure 4, cell viability was measured according to the concentration change of the plant extracted with different concentrations of ethanol at 24, 48 and 72 hours. At the lowest concentrations, no results were achieved, the cancer cells continued to grow. But PC3 cell line deaths were observed in measurements taken in the first 24 hours at 100 µg/ml and 50 µg/mL. By the end of 72 hours, there was half death. This means that measurements made in high concentrations create an anti-carcinogenic effect through the cancer line. Cytotoxic evaluation of *eruca vesicaria* for 24, 48 and 72 hour was compared with total phenol content. The cell viability test is similar according to the phenol amounts obtained in proportion to the total phenol analysis and HPLC analysis. It has been observed in this study that extracts having higher total phenol content leads to cytotoxic activity on fibroblast cells, in accordance with the theory. Cytotoxicity activity and total phenol content is found as closely related with the extraction parameters such as extraction time, extraction medium system and temperature. It can be concluded that optimization of extraction plays a key role in properties of the extract, that is also relevant with its.

4. Discussion

The present study aimed to optimize the extraction process of *Eruca vesicaria* and evaluate its effects on total phenolic content (TPC), phenolic compound composition, antimicrobial activity, and cytotoxicity. Our findings revealed a distinct correlation between the ethanol concentration used in the extraction process and the yield, phenolic content, and biological activities of the extracts. The results suggest that ethanol concentration significantly impacts the solubility of phenolic compounds, influencing the extract's overall properties.

The extraction yields varied with ethanol concentration, with the 50% ethanol extraction yielding the highest (21.18%), followed by 90% (19.02%) and 10% (18.12%). This outcome reflects the solubility behavior of polar phenolic compounds, which are more effectively extracted in a moderately polar solvent such as 50% ethanol. The lower yield at 90% ethanol suggests a reduced efficiency in extracting polar phenolic compounds, likely due to the decreased polarity of the solvent. This observation aligns with previous studies, where optimal extraction conditions for phenolic compounds were found to depend on the balance between solvent polarity and phenolic solubility (Elsadek et al., 2021).

TPC analysis corroborated these findings, with the 50% ethanol extract showing the highest phenolic content (67.01 mg GAE/g DW), while the 90% ethanol extract exhibited the lowest (57.66 mg GAE/g DW). The observed decrease in TPC at higher ethanol concentrations suggests that while a more nonpolar solvent may enhance the extraction of some compounds, it is less efficient for phenolic extraction. This trend reflects the polarity-dependent solubility of phenolic compounds, which are primarily polar in nature. It is well-established that ethanol-water mixtures provide a more balanced polarity, thereby facilitating a higher extraction of phenolics (Xia et al., 2021).

HPLC analysis further elucidated the effect of ethanol concentration on the types of phenolic compounds extracted. While all extracts displayed similar phenolic profiles, the peak intensities varied, indicating that ethanol concentration influences the relative amounts of different phenolics. Notably, the 50% ethanol extract had a more balanced phenolic composition, as seen in the chromatographic peaks. This suggests that an intermediate solvent polarity optimally extracts a broader range of phenolic compounds. The longer retention times in the 10% and 90% ethanol extracts may also indicate that solvent polarity impacts the interaction of phenolics with the column, leading to varied retention behavior depending on the compound's structure and polarity.

The MIC assay demonstrated significant antimicrobial activity of the *Eruca vesicaria* extracts, particularly against L. monocytogenes and E. coli. The most potent antibacterial effect was observed in the 90% ethanol extract at a concentration of 5 mg/mL for E. coli and in the 50% ethanol extract for L. monocytogenes. This suggests that while 90% ethanol may not efficiently extract total phenolics, it is effective in isolating specific bioactive compounds with potent antibacterial activity. The differential antimicrobial effects observed between the two bacteria further emphasize the complexity of the bioactive compounds in *Eruca vesicaria*, where specific compounds may exhibit varying degrees of activity depending on the target microorganism. The lower efficacy observed at lower concentrations indicates that a threshold concentration of bioactive compounds is necessary for antimicrobial action.

In terms of cytotoxicity, the MTT assay revealed promising anticancer potential of the *Eruca vesicaria* extracts. The 50% and 90% ethanol extracts exhibited significant cytotoxic effects on prostate cancer cells (PC3), with a dose- and time-dependent reduction in cell viability. The highest cytotoxicity was observed in the 50% ethanol extract, which correlates with its higher TPC, and phenolic diversity as revealed by HPLC. These findings suggest that the phenolic compounds extracted at 50% ethanol play a critical role in the extract's anticancer activity. The similarity between the phenolic content and cytotoxicity results aligns with previous studies, where higher phenolic content has been associated with enhanced cytotoxic and antioxidant activities (Chiemchaisri et al., 2021).

The cytotoxic effect on PC3 cells contrasts with the minimal impact on HEK-293 cells, indicating selective anticancer activity. The bar shown in blue in Figure 4, called control, represents HEK-293 cells. Since no death due to the extract was observed in the experiments performed here, it is shown as a single bar to simplify the graph. This selectivity suggests that the phenolic

compounds in *Eruca vesicaria* could serve as potential chemo preventive agents, targeting cancer cells while sparing normal cells. The time-dependent increase in cytotoxicity highlights the importance of both extract concentration and exposure time in maximizing anticancer efficacy.

In conclusion, our study demonstrates the critical role of ethanol concentration in modulating the extraction efficiency, phenolic content, and biological activities of Eruca vesicaria extracts. The 50% ethanol extract consistently showed superior performance across all assays, suggesting it as the optimal extraction condition for maximizing bioactive phenolic yield and biological efficacy. Future studies should focus on further characterizing the individual phenolic compounds responsible for the observed antimicrobial and anticancer activities and exploring their mechanisms of action. The optimization of extraction parameters holds significant promise for enhancing the therapeutic potential of *Eruca vesicaria* in bioengineering applications.

5. Conclusion

In the studies, the extraction of *Eruca vesicaria* was done with 3 different polarity solvent groups. Firstly, standardization of extraction was done. These were made in the form of ethanol concentrations of 10%, 50% and 90% over the same period and under the same ambient conditions. Phenolic substance change in the content of the obtained plant extracts was measured by HPLC. The results show that phenolics were obtained in the same but different proportions. Total phenol quantities were determined by spectrophotometric method. A different result was obtained according to the amount of concentration, which was a proportional result compared to the HPLC results. HPLC analyses showed the differences in the contents of extracts obtained with changing extraction conditions. At the same time, the effect of this phenolic change on gram-positive and gram-negative bacteria has been tested on different bacteria using the microplate test. As a result, the presence of antibacterial properties of plant extract in different concentrations was tested. Although the concentration of extraction had little effect on antibacterial property, concentrations of agents prepared in different proportions showed antibacterial property. All the agents prepared in high concentrations killed the bacteria. Finally, the anti-carcinogenic effect on prostate cancer was measured using the MTT test. The plant extracted at a high alcohol concentration showed an effect on PC3, a prostate cancer line, when prepared with a high concentration. Direct proportional results were obtained compared to total phenol determination and microplate studies. Samples prepared in high concentration were measured to have anticancer and antibacterial properties.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	M.E.U.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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BİR MERMER OCAĞINDAKİ TEHLİKE VE RİSKLERİN DEĞERLENDİRİLMESİ

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Özet: Türkiye'deki mermer ocaklarında potansiyel tehlike ve riskler çeşitli faktörler sonucu oluşur. Bunlar arasında iş güvenliği standartlarının ihlali, ekipman arızaları, jeolojik yapıdaki değişimler, işçi eğitim eksikliği ve çevresel etkiler gibi unsurlar yer almaktadır. Bununla birlikte; mermer ocakları gibi endüstriyel ortamlarda meydana gelen iş kazaları çeşitli nedenlere bağlı olabilir. Bunlar arasında düşmeler, ekipman arızaları, kaya düşmeleri, kimyasal maruziyetler ve yorgunluk gibi faktörler yer alabilir. L matris risk değerlendirme yöntemi, endüstrinin birçok alanında kullanılan bir yönetim aracıdır. Bu yöntem, riskin olasılığını ve etkisini bir matris üzerinde değerlendirerek risklerin önceliklendirilmesini sağlar. L matris risk değerlendirme yöntemi, bu faktörlerin her birinin olasılığını ve etkisini belirleyerek bir matris üzerinde görselleştirir. Olasılık ve etki değerleri, düşükten yükseğe doğru derecelendirilir ve bu değerler çarpılarak risk seviyesi hesaplanır. Bu yöntem, mermer ocaklarındaki tehlike ve riskleri tanımlamak, önceliklendirmek ve yönetmek için etkili bir araç olabilir. Ancak, tam ve kapsamlı bir değerlendirme için işletmelerin uzmanlarla işbirliği yapması ve yerel yönetmeliklere uygun olarak hareket etmeleri önemlidir. Bu çalışma, Türkiye'deki bir mermer ocağındaki tehlike ve riskleri L tipi risk değerlendirme yöntemi ile analiz etmiştir. Elde edilen sonuçlar, mermer ocağında sondaj ve açık ocak işletme alanlarında ağır iş makinelerinin devrilmesi, kaya düşmesi ve büyük parçaların kopması gibi tolere edilemeyen risklerin ölümcül sonuçlar doğurabileceğini göstermektedir. Açık ocak alanındaki diğer belirgin riskler arasında makine ekipman çarpması, parça düşmesi ve toz gibi unsurlar yer almaktadır. Ayrıca, hijyen konuları da açık ocak ve genel işletme alanlarında dikkate değer bir risk olarak değerlendirilmiştir. Öte yandan, arızalar ve trafik kazaları, tolere edilebilir ve hafif risk grubu içinde sınıflandırılmıştır. Bu değerlendirme, iş güvenliğini artırmak için gerekli önlemlerin alınmasına yönelik önemli bir temel oluşturmaktadır. Bu kapsamında Türkiye'de yer alan bir mermer ocağındaki tehlike ve riskler L tipi risk değerlendirme yöntemi kullanılarak tanımlanmış ve risk değerlendirilmesi gerçekleştirilmiştir.

Anahtar kelimeler: Maden, Mermer ocağı, Risk değerlendirme, L tipi matris, Tehlike, Risk

Assessment of Hazards and Risks in a Marble Quarry

Abstract: Potential hazards and risks in marble quarries in Türkiye occur as a result of various factors. These include violations of occupational safety standards, equipment failures, changes in geological structure, lack of worker training and environmental impacts. However; occupational accidents occurring in industrial environments such as marble quarries can be due to various reasons. These may include factors such as falls, equipment failures, rock falls, chemical exposures and fatigue. The L matrix risk assessment method is a management tool used in many areas of industry. This method enables prioritisation of risks by evaluating the probability and impact of the risk on a matrix. The L matrix risk assessment method determines the probability and impact of each of these factors and visualises them on a matrix. The probability and impact values are ranked from low to high and the risk level is calculated by multiplying these values. This method can be an effective tool for identifying, prioritising and managing hazards and risks in marble quarries. However, for a complete and comprehensive assessment, it is important that enterprises cooperate with experts and act in accordance with local regulations. This study analyzed the hazards and risks in a marble quarry in Türkiye with the L-type risk assessment method. The results obtained show that intolerable risks such as tipping over of heavy machinery, falling rocks and breaking off large pieces in marble quarry drilling and open pit mining areas can have fatal consequences. Other significant risks in the open pit area include elements such as machinery and equipment impact, falling parts and dust. In addition, hygiene issues were considered a significant risk in open pit and general operating areas. On the other hand, breakdowns and traffic accidents are classified in the tolerable and mild risk group. This evaluation forms an important basis for taking the necessary measures to increase occupational safety. In this context, hazards and risks in a marble quarry in Türkiye were identified and risk assessment was carried out using the L-type risk assessment method.

Keywords: Mine, Marble quarry, Risk assessment, L type matrix, Hazard, Risk

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1. Giriş

Günümüzde, Türkiye mermer üretimi bakımından dünya üreticileri arasında yer almaktadır. Dünyada birçok ülkeye mermer ihraç eden Türkiye, hammadde bakımından zengin mermer yatakları ve gelişmiş teknolojik altyapıya sahiptir. Bu sayede birçok ülkeye kaliteli ve çeşitli mermer türleri sunmaktadır. Bu türler özellikle ülkemizde Ege, Marmara ve Doğu Anadolu bölgelerinde bulunmaktadır. Bu mermerlere olan ilgi yüksektir. Bunun nedeni mermerlerin; kalitesi, çeşitliliği ve rekabetçi fiyatlarıyla dünya pazarında talep görmesinden kaynaklanmaktadır (Sırakaya ve Kasap, 2019; Önder ve ark., 2022). Ayrıca başka bir nedeni olarak mermer ve travertenlerin doğada bolca bulunan, işletilmesi kolay, dünya genelinde önemli bir pazar payı olan endüstriyel maden kategorisinde yer almasıdır. Maden kategorisinde önemli bir yerinin olması yüksek rezervlere sahip olmasından ileri gelmektedir. Toplam rezerv bakımından Türkiye 5,2 milyar m^3 (13,9 milyar ton) miktara sahiptir. Dünya mermer potansiyelinde yaklaşık %40'ın oluşturmaktadır. Ancak %1'lik bir kısmı bu potansiyel içinde kullanılmaktadır. Kullanıma bağlı olarak mermer üretimi özellikle 1980'li yıllardan itibaren hızla artış göstermiştir. Artışa bağlı olaraktan Türkiye, mermer üretiminde dünyada 7. sırada, mermer ihracatında ise 8. sırada yer almayı başarmıştır. Mermer işletimi sektörel bakımdan 116'sı kamu ve 447'si özel olmak üzere toplam 563 işletme bulunmaktadır. Bu işletmelerde çalışan toplam 5968 kişinin 1021'i kamuya, 4947'si de özel sektöre ait iş yerlerinde çalışmaktadırlar. 2002 yılına gelindiğinde Türkiye 3.105.000 ton mermer üretmiş ve bunun 820.000 tonunu ihraç etmiştir. Mermer üretiminde ve ihracatında daha iyi duruma gelebilmemiz için mermer üreten ve ihraç eden firmalara kolaylıklar tanınmalı ve çalışanları için güvenilir ortamlar sağlanmalıdır. Bunun için ülkemiz mermerlerinin uluslararası marka hâline gelmesi için gerekli tanıtım ve girişimler ilgili kuruluşlarca mutlaka yapılmalıdır. Bu tanıtımların ön plana çıkması için daha az riskler, tehlikelere maruz bırakılarak güvenli iş ortamlarında çalışanlara çalışma ortamı sağlanmalıdır (Çetin, 2003).

Mermer birçok sektörde kullanılabilen ve nüfusun artması ile kullanım alanları daha da genişleyen bir ürün haline gelmiştir. Türkiye; ham ve yarı işlenmiş mermer ve traverten gibi ürün kategorisinde ihracatının yapılması noktasında dünya çapında ilk sıralarda yer almaktadır. Türkiye'de de üretilen mermerlerin bir kısmı kullanılırken bir kısmı da ihraç edilmektedir. Bu yüzden üretilen mermer ve travertenlerin yaklaşık % 30'u her yıl ihraç edilmektedir (DPT, 2001). Mermer ihracatının başında Çin önemli bir yer tutmaktadır. Ham ve yarı işlenmiş ürün olarak üretilen ülkemizde mermer ve traverten ihracatının yapılması noktasında dünya çapında ilk sıralarda yer almaktadır (Adıgüzel ve Şengüler, 2019). Bu durumun en önemli nedeni her geçen yıl üretimi ve tüketimi giderek büyüyen bir sektör haline gelmesidir. Türkiye'de 1980 yılında birkaç milyon dolar olan mermer (doğal taş) ihracatı, 2013 yılında 2,2 Milyar $ seviyesine ulaşmıştır. 2016 yılında 1,8 Milyar $ düzeyinde düşüş yaparak devam etmiştir. 2016 yılından 2017 yılına geçişte 2 Milyar $ seviyesine çıkarak artış göstermiştir. 2023 yılı itibari ile Türkiye doğal taş üretim ve ihracat bakımından dünyada ilk 5 ülke arasında olmayı başarmıştır. Bu yıl kapsamında Türkiye'nin 10 Milyar $ olarak doğal taş ihracat hedefi ön görülmüştür. İhracat hedefi olan seviyeleri 2023 yılında doğal taş sektöründe öngörmek, bu seviyeyi korumak ya da daha yukarı taşımak için yöntemler geliştirilmiştir (Altındağ, 2018; Şahin Demir ve ark., 2022).

Mermer ocaklarında mermer işletimi tehlikeli ve iş güvenliği fazlaca gerektiren bir iş koludur. Bu iş kolunda elde edilecek ürünler daha kaliteli ve düşük maliyetlerde işletilerek gerçekleştirilmesi hedeflenmektedir. Ancak, mermer ocaklarının faaliyet gösterdiği alanlarda, endüstriyel iş kazaları ve sağlık sorunları gibi potansiyel riskler de bulunmaktadır (Ilgaz, 2019). Özellikle, mermer ocaklarında çalışan işçiler, günlük işlerini yerine getirirken çeşitli tehlikelerle karşılaşmaktadırlar (Gümüş ve Akkoyun, 2006; Çakıroğlu, 2007; Dike, 2009). Bu tehlikeler, kaya düşmeleri, iş ekipmanı arızaları, kimyasal maruziyetler, ergonomik sorunlar, çalışma ortamı sıcaklığı ve toz maruziyeti gibi unsurları içermektedir. Bu riskler, işçilerin sağlığı ve güvenliği üzerinde ciddi etkilere sahip olabilir ve uzun vadeli sağlık sorunlarına yol açabilir (Bacak, 2002; Bajpayee ve ark., 2004; Karra, 2005; Dolmaz, 2018).

Bu nedenle, mermer ocaklarında faaliyet gösteren işletmelerin, iş sağlığı ve güvenliği standartlarını yükseltmeleri ve işçilerin güvenliğini sağlamak için etkili önlemler almaları kritik öneme sahiptir (Özçelik, 2013). Bu önlemlerin alınması için öncelikle, mevcut tehlikelerin ve risklerin tam olarak anlaşılması ve değerlendirilmesi gerekmektedir (Ağca, 2010; Eleren ve Ersoy, 2011; Tantoğlu, 2016; Yavuz, 2018).

Bu bağlamda, L matris risk değerlendirme yöntemi, iş yerlerindeki potansiyel tehlikeleri ve riskleri belirlemek, önceliklendirmek ve yönetmek için etkili bir araç olarak öne çıkmaktadır. Bu yöntem, riskin olasılığını ve etkisini bir matris üzerinde değerlendirerek risklerin önceliklendirilmesini sağlar. Bu, işletmelere, sınırlı kaynakları en etkili şekilde kullanarak en yüksek riskli alanlara odaklanmalarına olanak tanır (Sarıkaya, 2014). Mermer ve daha birçok madencilik alanında hatta madencilik alanları dışında oluşabilecek risklerin ortaya konulmasında L tipi matris yöntemi yaygın olarak kullanılmaktadır. Madencilik alanları dışında tekstil işletmelerinde, okullarda deprem sonrası oluşabilecek risklerin belirlenmesinde, balıkçı gemilerinde oluşabilecek farklı faktörler etkisi altındaki riskleri belirlenmesinde önemli bir role sahiptir (Soykan, 2018; Bayraktar ark., 2019; Karaman ve Topaksu, 2020). Madencilik alanlarında ise genellikle ağır iş makinalarının oluşturduğu ya da cevher üretimi

sırasında izlenen farklı ünitelerinin her birinde ayrı ayrı kullanarak risk değerlendirme analizi yapılabilir (Korkmaz, 2020; Keskin ve ark., 2020).

Bu çalışmanın amacı, Türkiye'de var olan mermer yataklarını ileri teknolojiler kullanılarak, ülkenin dünya mermer pazarındaki konumunu artırmaktadır. Türkiye'deki mermer üreticileri, üretimlerinde son teknolojileri kullanmaları, yüksek kaliteli ve estetik görünümlü mermerler üretmesini sağlayacaktır. Bu teknolojik gelişmeler, Türkiye'nin dünya mermer pazarındaki konumunu güçlendirecektir. Türkiye'deki fazlaca bulunan mermer ocaklarının işletiminin daha güvenli işletilmesi oluşabilecek iş kazalarının önüne geçerek daha düşük maliyetlerde çalışma yapılmasını sağlayacaktır. İşletme maliyetleri oluşabilecek riskleri önceden belirlemek ve gerekli önlemler alarak maliyetin düşmesine ve insanların zarar görmesini engellemede L tipi matris yöntemi çok önemli bir yere sahiptir. Bu yöntemin mermer ocağında kullanılması için öncelikli olarak mermer işletim ocaklarında mevcut tehlikeler ve riskler tanımlanarak ortaya çıkarılması gerek. Daha sonra L tipi matris yöntemi kullanılarak olası riskler değerlendirilmiştir. Bu değerlendirmeyi bir rehber olarak kullanmak işletmelere iş sağlığı ve güvenliği önlemlerini geliştirmek için yol gösterici olmaktır. Bu şekilde, mermer ocaklarında çalışanların sağlığı ve güvenliği üzerindeki risklerin azaltılması ve endüstriyel iş kazalarının önlenmesi, işletme maliyetlerini en alt seviyelerde tutmaya katkı sağlar.

2. Materyal ve Yöntem

2.1. Materyal

Bu çalışmada, özel bir mermer ocağında tehlike ve riskler belirlenmiştir. Mermer ocağında; sondaj, tüm ocak işleri, mermer blok kesimi, sayalama, iş makineleri, mermer blok stoklama, akaryakıt ikmal ve taşıma, bakım onarım, basınçlı tüpler, idari binalar, elektrik. Ocak çevresinde yer alan tehlike ve riskler ele alınmıştır. Müşteri talebine göre blok halinde mermer ihtiyacı da sağlanmaktadır. Blok halinde gelen mermerler, ihtiyaca göre katrak makinesinde veya S/T makinesinde kesilmektedir. Sonrasında fabrikada bulunan bant makinelerinde işlenerek müşteriye sunulmaktadır.

2.2. Metot

Çalışmada alan olarak seçilen mermer ocağında ilk önce işyerine özel tehlike ve riskler saha kontrolleri ve çalışanlar ile yapılan görüşmeler sonucunda tespit edilmiştir. Yöntem riskleri sistematik olarak değerlendirmek için kullanılır. Mermer ocağında risklerin değerlendirilmesi için kullanılan L tipi matris yöntemi, iş güvenliği ve çevrenin korunması açısından önemlidir. Yöntem uygulanırken ilk olarak, mermer ocağındaki ekipman arızaları, düşme, kayma veya devrilme, toz ve gürültü maruziyeti, patlayıcı madde kullanımı, çalışanların sağlık sorunları, potansiyel tehlikeler vb. gibi durumlarda riskler belirlenmiştir. Bu riskler sonrasında çalışanlarda oluşabilecek sağlık sorunlarına karşı yöntemde yer alan olasılık ve etki derecelendirmesi her bir tehlike için olasılık (1-5 arası) ve etki (1-5 arası) derecelendirmesi yapılmıştır.

Olasılık olarak belirlenen: Tehlikenin gerçekleşme olasılığı (1: çok düşük, 5: çok yüksek), Etki: Tehlikenin sonucunda oluşabilecek zararın büyüklüğü (1: çok az, 5: çok büyük) etkilerine göre riskler sınıflandırılır. Daha sonrasında Risk Skoru Hesaplama yöntemi kullanılarak, Risk skoru, olasılık ve etki çarpımıyla hesaplanmıştır (eşitlik 1).

$$\text{Risk Skoru} = \text{Olasılık} \times \text{Etki} \quad (1)$$

Hesaplama sonrasında elde edilen risk skorlarına göre L tipi matris analizi oluşturulur. Yöntemde matrisin üç ana bölgesi bulunmaktadır. Bunlar;

Kabul Edilebilir Riskler: Düşük risk skorları (1-4),

Gözetim Gerektiren Riskler: Orta risk skorları (5-12),

Yüksek Riskler: Yüksek risk skorları (13-25),

olarak risk skorları oluşturulmuştur. Oluşan risk skorları sonrasında her bir risk kategorisine göre gerekli önlemler belirlenmiştir. Önlemler kapsamında düşük riskler sınıfında yer almışsa, izleme ve rutin kontroller, orta riskler sınıfında yer almışsa, eğitim, güvenlik ekipmanları ve prosedürlerin güçlendirilmesi, yüksek riskler sınıfında yer almışsa, acil önlem alınması, süreçlerin yeniden gözden geçirilmesi ve riskin minimize edilmesi gerekmektedir. Ocakta oluşabilecek riskler sürekli dinamik kapsamda yer almakta olup düzenli olarak takip, gözden geçirilmesi ve güncellenmesi gerekmektedir.

Bu yöntemi kullanarak, mermer ocağındaki riskleri sistematik bir şekilde değerlendirip, güvenli bir çalışma ortamı sağlamanız mümkün olacaktır.

2.2.1. Tehlike ve Risklerin Belirlenmesi

Mermer ocağı işletim sürecinde ocak çalışma düzeni, arazi şartları ve iklim durumu, ekipmanlar, çalışanlar vb. birçok tehlike ve bu tehlikeler sonrasında oluşan riskler yapılan saha incelemeleri sonrasında belirlenmiştir. Çalışanlar ile görüşmeler incelenmiş ve ocakta maruz kaldıkları tehlike ve riskler ile bunlara karşı alınan önlemler değerlendirilmiştir.

2.2.2. Risk Değerlendirilmesi

Bu çalışma kapsamında risk değerlendirme yöntemi olarak L tipi matris (5X5) yöntemi kullanılmıştır. Bu yöntemde; risk değeri olasılık ve şiddet değerinin çarpımı sonucu bulunmuştur (Eşitlik 2).

$$\text{Risk (R)} = \text{Olasılık (O)} \times \text{Şiddet (Ş)} \quad (2)$$

L tipi matris yöntemi kullanılırken Tablo 1 ve 2'de verilen bilgiler doğrultusunda puanlama yapılmıştır.

Tablo 1. Zararın gerçekleşme olasılığı (Olasılık) (Doğan ark., 2023)

	Skor	Olasılık (İhtimal)	Açıklama
Olasılık x Şiddet	5	Her gün	Çok Yüksek
	4	Haftada bir	Yüksek
	3	Ayda bir	Orta
	2	Üç ila altı ayda bir	Düşük
	1	Çok düşük	Hemen Hemen Hiç

Tablo 1'de L tipi matris yönteminde zararın gerçekleşme olasılığı 1'den 5'e kadar verilen skorlarla sıralanmıştır. Sıralamaya göre olasılıklar ve bu olasılıklara göre açıklamalar verilmiştir. Yer alan açıklamalarda her gün, haftada bir, ayda bir, üç ila altı ayda bir, çok düşük olarak tanımlanmaktadır. Bu olasılıklara karşı yapılan açıklamalar ise çok yüksek, yüksek, orta, düşük, hemen hemen hiç olarak belirtilmektedir.

Tablo 2'de ise; L tipi matris yönteminde Şiddet, 1'den 5'e kadar tehlikenin etkileri sıralanmaktadır. Şiddet ise birden çok ölümlü, ölümlü veya sürekli iş görmezlik, çok büyük maddi ve çevre kirliliği, ciddi yaralanma, meslek hastalığı, büyük maddi hasar, en az üç gün istirahat gerektiren yaralanmalar, maddi hasar, ilkyardım gerektiren küçük yaralanmalar, tamir altı maddi hasar, hasar ya da yaralanmaya neden olmayan kaza, iş saati kaybı olmayan olarak gruplandırılmıştır. Tehlikenin şiddetleri ise çok ciddi, ciddi, orta, hafif, çok hafif olarak belirlenmektedir (Doğan ark., 2023).

Tablo 2. Şiddet puanlama kriteri (Doğan ark., 2023)

	Skor	Şiddet	Açıklama
Etki (Şiddet)	5	Birden çok ölümlü, ölümlü veya sürekli İş Görmezlik Çok Büyük Maddi ve Çevre Kirliliği	Çok Ciddi
	4	Ciddi Yaralanma, Meslek hastalığı, Büyük Maddi Hasar	Ciddi
	3	En az üç gün istirahat Gerektiren Yaralanmalar, Maddi Hasar	Orta
	2	İlkyardım Gerektiren Küçük Yaralanmalar, Tamir altı Maddi Hasar	Hafif
	1	Hasar ya da yaralanmaya neden olmayan Kaza, İş Saati kaybı olmayan	Çok Hafif

Tablo 3. Olasılık ve şiddet (etki) değerlendirmesi (Doğan ark., 2023)

Risk matrisi		Zarar verme etki derecesi				
		Çok hafif	Hafif	Orta derece	Ciddi	Çok ciddi
Olasılık	Çok küçük 1	Düşük 1	Düşük 2	Düşük 3	Düşük 4	Düşük 5
	Küçük 2	Düşük 2	Düşük 4	Düşük 6	Orta 8	Orta 10
	Orta derece 3	Düşük 3	Düşük 6	Orta 9	Orta 12	Yüksek 15
	Yüksek 4	Düşük 4	Orta 8	Orta 12	Yüksek 16	Yüksek 20
	Çok yüksek 5	Düşük 5	Orta 10	Yüksek 15	Yüksek 20	Yüksek 25

L tipi matris yöntemi ile Tablo 1'de yer alan değerlere göre zararın gerçekleşme olasılığı ile Tablo 2'de yer alan etkinin (şiddet değerleri) çarpılması ile Tablo 3'de yer alan olasılık durumları ortaya çıkmıştır Böylece, olasılık ve şiddet dereceleri çarpılarak zarar verme etki derecesi bulunmuştur.

L tipi matris yöntemi kullanılarak Tablo 4'de zamana bağlı olarak değişen durumlara göre yapılması gerekenler verilmiştir. 1'den 25' e kadar risk değerleri numaralandırılmıştır. Aksiyon ve zaman planlamasın da her bir değere göre açıklayıcı bilgileri verilmiştir (Doğan ark., 2023).

Tablo 4. Risk Değeri Aksiyon ve Zamanlama Tablosu (Soykan 2018)

Risk Değeri Aksiyon ve Zaman Planlaması	
25	Tolere edilemez. İş geçici olarak durdurulmalı, en kısa sürede düzeltici faaliyetler planlanmalıdır.
15-20	Belirgin risk. Riski azaltacak faaliyetler kısa sürede planlanmalıdır. İş risk azaltılmadan başlatılmamalı veya kontrollü olarak devam etmelidir.
8-12	Dikkate değer (orta seviye) risk. Risk azaltma önlemleri zamanla alınmalıdır.
2-6	Tolere edilebilir risk. Ek kontroller gerekmiyor. Mevcut kontroller sürdürülmelidir.
1	Çok hafif risk. Faaliyet gerektirmiyor.

Katlanılamaz Risk: Belirlenen risk kabul edilebilir bir seviyeye düşürülünceye kadar işin başlatılmaması, devam eden bir faaliyet varsa derhal durdurulması gerekmektedir. Alınan önlemlere rağmen riski düşürmek mümkün değilse, faaliyetin engellenmesi gerekmektedir

Yüksek Düzey Risk: Çalışma risk azaltılmadan başlatılmamalıdır. Riskin azaltılması için dikkate değer kaynak ayrılması gerekebilir. İşin bu riske rağmen devam etmesi gerekiyorsa acil önlemler alınmalıdır.

Orta Düzey Risk: Risk seviyesini azaltmak için çaba harcanmalıdır. Fakat önleme maliyeti dikkatle ölçülmeli ve sınırlandırılmalıdır. Risk azaltma önlemleri belirlenen en kısa zaman periyodunda uygulanmalıdır. Şiddeti çok yüksek olabilecek orta seviye riskler söz konusu olduğunda; daha iyi önlemler alınabilmesi için olasılık değerlendirmesi bir kez daha yapılmalıdır.

Düşük Risk: Belirlenen risklerin ortadan kaldırılması için ek önlemlere ihtiyaç duyulmamaktadır. Mevcut önlemlerin sürdürülmesi ve sürdürüldüğünün denetlenmesi gerekmektedir

Önemsiz Risk: Belirlenen riskleri ortadan kaldırmak için önlem almaya ve gerçekleşecek faaliyetlerin kayıtlarını saklamaya gerek yoktur (Soykan 2018).

3. Bulgular ve Tartışmalar

L tipi matris yöntemi yüksek risk taşıyan birçok alanda kullanım imkanı bulmuştur. Bu çalışmada ise mermer işletimi yapılan bir sahada oluşan riskleri ortaya koymak için kullanılmıştır.

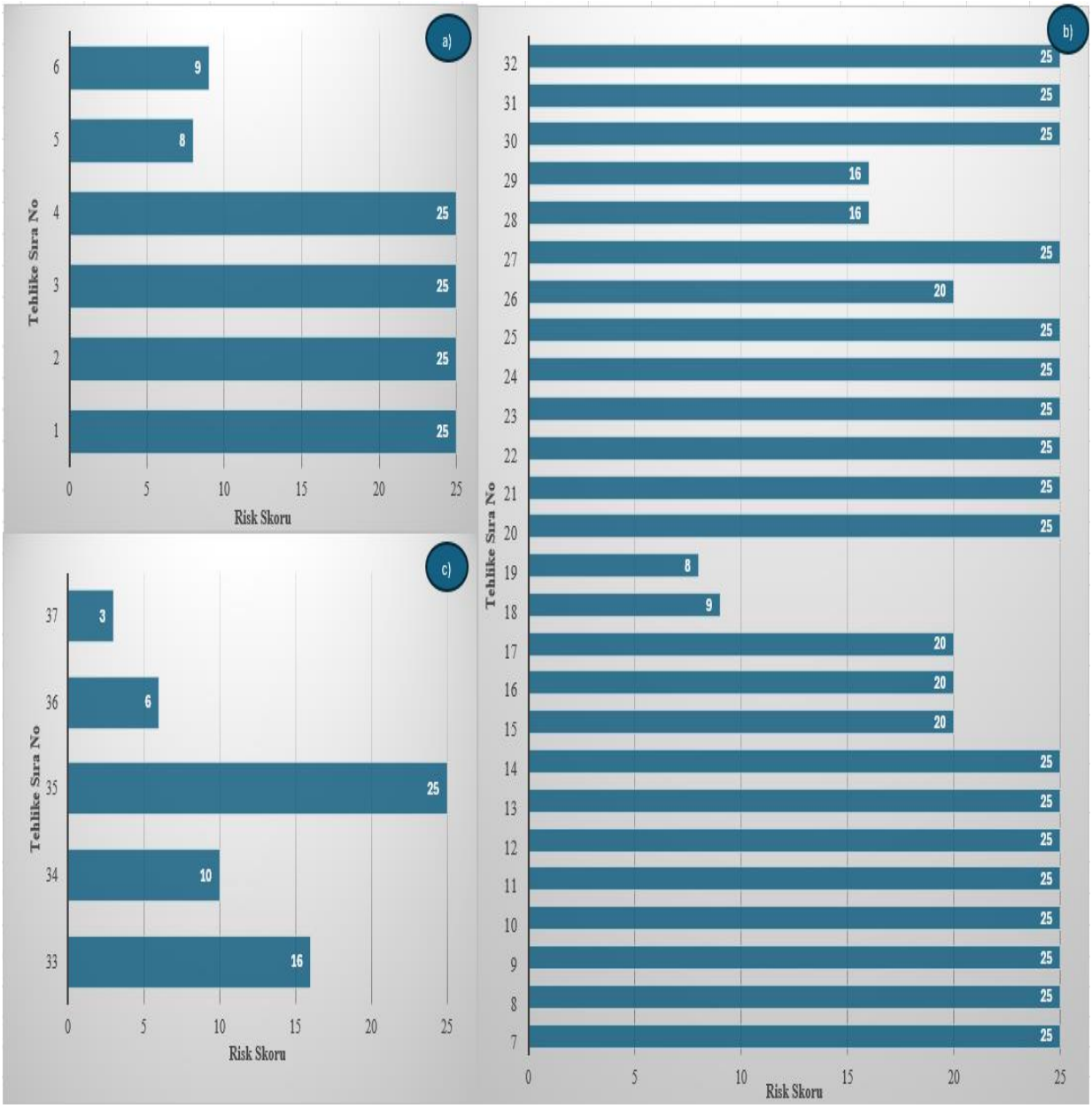
Şekil 1 a'da görüldüğü gibi sondaj iş akış sürecinde risk skoru en yüksek bulunan potansiyel tehlikelerin Sondaj makinesinin devrilmesi, yüksekten parça düşmesi olduğu görülmektedir. Açık ocak faaliyetlerinin değerlendirildiği Şekil 1b' de ise blok, sayalama, iş makineleri ve basınçlı tüpler ile ilgili iş kazaları yüksek risk değeri aldığı görülmektedir. Son olarak genel kısımdaki tehlikelere bakıldığında elektrik kaynaklı tehlikelerin yüksek risk değeri aldığı tespit edilmiştir (Şekil 1c).

Nitekim SGK iş kazası istatistiklerine bakıldığında da mermer faaliyet alanında 2022 yılında mermer taş kesimi ve işlenmesi sırasında meydana gelen ezilme, düşme ve kesilme, makine ekipman kullanımı gibi risklerden kaynaklanmaktadır. Bu durum çalışma kapsamında elde edilen sonuçları desteklemektedir.

L tipi matris yönteminin yanı sıra risk analizinde Fine Kinney yönteminde yaygın olarak kullanılan yöntemler arasında yerini almıştır. Her iki yöntem içinde özellikle sahada çalışan makinalar kapsamında oluşan risklerin belirlenmesinde etkili yöntemler olarak kullanılmıştır. Bu yöntemler sayesinde risklerin belirlenmesi ve tehlikelere karşı alınması gereken önlemler, yapılması gereken düzenlemeler belirlenmiştir (Korkmaz, 2020). Yapılan bir çalışmada L tipi matris yöntemi kullanımı sayesinde ocak içerisinde oluşabilecek tehlikelerin önceden belirlenmesinde kullanılmıştır.

L tipi matris yöntemi sayesinde başka bir çalışmada yer altı metalik madencilik işlemlerinde cevherin işletilmesinde geçen tüm işlemler sürecinde risk değerlendirmeleri yapmak için ve çalışma alanına ait karakteristik özelliklerin ortaya konulması sürecinde kullanılmıştır (Maiti, 2013; Keskin ve ark., 2020). Yine gürültü ve titreşim gibi yeraltı işletme alanı içerisinde oluşan riskler belirlenmiştir. Kullanılan L tipi matris sayesinde tespit edilen tehlikelerin oluş kaynağı, düzeyi gruplandırılmış ve analiz edilmiştir (Vermaas ark., 2007; Tezölmez, 2019). Yapılmış olan birçok çalışma için L tipi matris yönteminin kullanım alanları ve amaçları ortaya konulmuştur. Bu ve geçmişte yapılmış birçok çalışma için L tipi matris yöntemi kullanılarak risklerin düzeyleri, sınıflandırılması yapılmış ve yapılmaya çalışılmıştır. Daha sonra belirlenen risklere göre alınması gereken önlemlerde ortaya konulmuştur (Selçuk ve Selim, 2018; Doğan ve Keskin, 2023).

Bu çalışmada, yapılan tüm çalışmalar gibi, öncelikle mermer ocağında yer alan riskler ortaya konulmuştur. Meydana gelebilecek risklerin tespit edilmesi ile risk çeşitleri ve tanımları belirlenmiştir. Belirlenen risklere karşı kanunlarda yer alan mevzuatlar kapsamında alınması gereken tedbir ve önlemler ortaya konulmuştur. Değerlendirme ile hangi önlemlerin alınması gerekliliği de ortaya konulmuştur (Ek Tablo).



Şekil 1. Oluşan tehlikelerin risk değerlendirilmesi.

4. Sonuç

Bu çalışma kapsamında Türkiye'de yer alan bir mermer ocağındaki tehlike ve riskler tanımlanarak L tipi risk değerlendirme yöntemi kullanılarak risk değerlendirilmesi gerçekleştirilmiştir. Buna göre alınması gereken önlemler aşağıda belirtilmiştir:

- Çalışanlara temel İSG eğitimi ve mesleki eğitim verilmelidir.
- KKD kullanılması ile ilgili eğitim verilmelidir.
- Çalışanlara uygun KKD temin edilmelidir.
- Çalışma alanı ve çalışanların gözetimi yapılmalıdır.
- Çarpma ya da düşmelere karşı mutlaka baret ve diğer kişisel koruyucular kullandırılmalıdır.
- Çalışanlara olası kaza ve sonuçlarını da kapsayan hizmet içi eğitimler düzenli olarak verilmelidir.
- Sondaj makinelerinin periyodik bakım ve kontrolleri düzenli olarak yapılmalıdır.
- Çalışanlara iş sağlığı ve güvenliği (İSG) konularında kapsamlı bir temel eğitim sağlanması büyük önem taşımaktadır. Ayrıca, mesleki becerilerin geliştirilmesi amacıyla çeşitli eğitim programları uygulanmalıdır. Bu eğitimlerin düzenli olarak tekrarlanması, çalışanların bilgi ve yetkinliklerini artırarak iş yerindeki güvenliği sağlamada önemli bir rol oynayacaktır. Çeşitli eğitim yöntemleri ve içerikleri kullanılarak, çalışanların motivasyonu artırılmalı ve öğrenme süreçleri desteklenmelidir. Bu sayede, hem iş verimliliği artacak hem de güvenlik kültürü güçlenecektir.
- KKD kullanımı hassasiyetle takip edilmelidir.
- Çalışanlara mesleki eğitim ve sertifikaları tamamlanmadan iş başı yaptırılmamalıdır.

- Makine ve teçhizatin periyodik bakımları Operatörlük belgesine sahip olmayan çalışanların iş makinelerini kullanmasına izin verilmemelidir, düzenli olarak yapılmalıdır.
- Saha denetim ve gözetimi titizlikle yapılmalıdır.
- Gerekli bilgi, yön ve uyarı levhaları bulundurulmaldır.
- Gece çalışmalarında İş Güvenliği tedbirleri tam olmalıdır. Alanında uzmanlık gerektiren işler için teknik yeterlilik ve ilgili belgeye sahip personel olmadan tamirat ve hazırlık işi yaptırılmamalıdır.
- Aydınlatma yeterli olmalıdır.
- Sıfır döküm yapılmamalı geriden emniyetli mesafeden döktürülmelidir.
- İstifleme en fazla ikili yapılmalıdır. Döküm sahasında sıfır döküm yapılmamalı, geriden emniyetli bir mesafeden toprak döküm sahasındaki ilgili alana döktürülmelidir.
- Stok sahasında çalışan operatörlerine gerekli eğitimler verilmelidir.
- Stok alanında potansiyel tehlike ve iş yeri kurallarını içeren gerekli bilgi, uyarı ve yön levhaları olmalıdır.
- Ocak harici gelen müşterilerin yükleme ve saha çalışması esnasında kamyon ve iş makinelerine 25 metreden fazla yaklaşmalarına müsaade edilmemelidir.
- Yakıt tankerleri ve diğer teçhizatın periyodik olarak bakım ve kontrolü düzenli olarak yapılmalıdır.
- Çalışanlara yangın, sabotaj vs ile ilgili eğitim ve tatbikatlar yaptırılmalıdır.
- Yangın söndürme sistemlerinin periyodik bakım ve kontrolleri yapılmalıdır.
- Çalışma alanı içerisinde oluşabilecek yangınlara karşı yönetmeliklerde yer alan sayı ve vasıflarda yangın tüpü, söndürme düzeneği, eğitim almış yeterli sayıda personel bulundurulması gerekmektedir.
- İş yeri ve tesisler için gerekli uyarı, alarm sistemleri ile iç ve dış güvenliğin sağlanması için gerekli ve yeterli sayıda güvenlik personeli olmalıdır.
- Çalışanlara düzenli aralıklarla ortam tehlikeleri ve korunma yolları hakında eğitim verilmelidir.
- Mermer ocağında makine ve teçhizatın periyodik bakımları, hem güvenlik hem de verimlilik açısından son derece önemlidir. Bakımların düzenli yapılması, ekipmanın ömrünü uzatır, arızaları önler ve üretim süreçlerinin aksamadan devam etmesini sağlar. Ayrıca, iş kazalarının önlenmesi açısından da kritik bir rol oynar. Bu nedenle, bakım takvimlerine sadık kalmak büyük önem taşır. Ocak içi çalışma alan ve güzergahları düzgünli ve temiz tutulmalıdır.
- Ocak içi yön ve uyarı işaret ve levhaları tam ve eksiksiz olmalıdır.
- İş makineleri içerinde yer alan kabinlerde çalışan operatörlerden başka bir kimsenin bulunmasına izin verilmemelidir.
- Operatörlük belgesi olmayan kişilerin bu makineleri kullanması ve binmesine izin verilmemelidir.
- Basınçlı tüpler muhafaza altına alınmalıdır.
- Yangın, sabotaj ihtimaline karşı gerekli önlemler alınmalıdır.
- Çalışanların ve görevli personelin hijyen kurallarına uymaları sağlanmalıdır.
- Mutfak, tuvalet, banyo ve koğuşlar ile ofisler düzenli olarak temizlenmelidir.
- Görevlilere gerekli temizlik ve hijyen malzemeleri sağlanmalıdır.
- Kullanılan yalıtkan izolasyon eldiven, anti statik iş botları ve ayakkabı gibi kişisel koruyucu ekipmanları iş tanımına uygun, sağlam ve çalışanların kullanacağı sayıda olmalıdır.
- Alanında uzmanlık gerektiren işler için teknik yeterlilik ve ilgili belgeye sahip personel olmadan tamirat ve hazırlık işi yaptırılmamalıdır.
- Çalışma ortamı ve çevresi teknik olarak güvenliği sağlanmadan çalışmaya başlanılmamalıdır.
- Çalışma sırasında çalışma alanı ile kontrol sağlayan alanlar arasında irtibat kesilmesi ile çalışma anında sonlandırılmalıdır.
- Kablo ve elektrik malzemesi iyi izalasyonlu, yalıtkan olmalıdır.

Yukarıda belirtilen önlemlerin alınması sonucunda bütün rirskler tolere edilebilir seviyeye gelecektir.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	D.D.Ş.	H.E.
K	50	50
T	50	50
Y	50	50
VTI	50	50
VAY	50	50
KT	50	50
YZ	50	50
KI	50	50
GR	50	50
PY	50	50
FA	50	50

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler. Yazarlar çıkar çatışması yaratabilecek herhangi bir finansal destek veya ilişki içerisinde değildir.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

Destek ve Teşekkür Beyanı

Yazarlar, desteklerinden dolayı ilgili mermer ocağı firmasına teşekkür eder.

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TRANSFER LEARNING FOR TURKISH CUISINE CLASSIFICATION

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Abstract: Thanks to developments in data-oriented domains like deep learning and big data, the integration of artificial intelligence with food category recognition has been a topic of interest for decades. The capacity of image classification to produce more precise outcomes in less time has made it a popular topic in computer vision. For the purpose of food categorization, three well-known CNN-based models—EfficientNetV2M, ResNet101, and VGG16—were fine-tuned in this research. Moreover, the pre-trained Vision Transformer (ViT) was used for feature extraction, followed by classification using a Random Forest (RF) algorithm. All the models were assessed on the TurkishFoods-15 dataset. It was found that the ViT and RF models were most effective in accurately capturing food images, with precision, recall, and F1-score values of 0.91, 0.86, and 0.88 respectively.

Keywords: Food classification, Deep learning, Convolutional neural network, Image classification, Transfer learning, ViT.

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1. Introduction

The problem of food recognition in still images has recently gained attention in the field of computer vision (Kiourt et al., 2020). While several benchmark datasets have been developed, featuring sample images of globally popular foods, a detailed analysis reveals a notable underrepresentation of Turkish cuisine. Despite the richness and diversity of Turkish dishes, they are scarcely represented in these datasets. A review of datasets created for food recognition indicates that there is only one dataset available that includes Turkish dishes. Consequently, the number of studies focusing on Turkish foods is insufficient, highlighting a clear need for more study to enhance the accuracy and applicability of food recognition systems for diverse culinary traditions.

The application of deep learning has significantly advanced the expanding field of computer vision, particularly in the context of image recognition tasks (Chai et al., 2021). A critical area of interest among these is food image recognition, which has emerged as a result of its extensive applications in health monitoring, dietary management, and interactive cooking guides (Chen et al., 2020; Zhang et al., 2023) Nevertheless, the complexity and diversity of food items, which are significantly different across various cultures and cuisines, present a challenge. This diversity requires image recognition systems that are scalable, versatile, and robust, and that can adjust to the variety of food presentation styles and appearances.

The initial studies on food recognition from images utilized manually created visual features and performed food classification based on these attributes (Yang et al., 2010; Bossard et al., 2014; Beijbom et al., 2015). For example, Yang et al. (2010) proposed a representation that encodes the binary relationships of food ingredients based on local features and used Support Vector Machines (SVM) for classification. In another study, Bossard et al. (2014) introduced a classification approach based on identifying distinctive image parts using the Random Forest method. Beijbom et al. (2015) considered incorporating the menus of relevant restaurants by utilizing the location information of images to enhance recognition success.

Recent research has focused on leveraging the capabilities of Convolutional Neural Networks (CNNs) and domain adaptation techniques to enhance the accuracy and efficiency of food recognition systems. For instance, the study by Kayıkçı et al. (2019) demonstrates the application of CNNs in classifying Turkish cuisine on mobile platforms, highlighting the adaptability of deep learning models to function within the constraints of mobile devices while maintaining high accuracy. Meanwhile, Kawano and Yanai (2015) focused on expanding food image datasets through domain adaptation, integrating existing categories to create more comprehensive datasets. This approach not only creates culturally diverse food recognition systems but also reduces reliance on manual labeling through crowdsourcing. The study uses a "foodness" classifier and Adaptive SVMs to refine and expand food image datasets, enhancing their quality and applicability to a wider range of food categories, broadening the scope of food recognition systems.

Suddul and Seguin (2023) focuses on using AI, particularly computer vision and deep learning, for food type classification. The authors employed a dataset of over 16,000 food images spanning 11 categories and utilized data augmentation to address class imbalance. Three models were tested: CNN from scratch, transfer learning with InceptionV3, and transfer learning with EfficientNetV2. Among these, EfficientNetV2 achieved the best results, with a validation accuracy of 94.5% and an F1-score of 94.7%. Data augmentation, dropout, and early stopping techniques were applied to prevent overfitting. However, the dataset used in this study contains fewer food categories compared to the dataset I employed in my work.

Boyd and et al. (2024) investigates CNN architectures for fine-grained food image recognition, classifying 20 individual food items. The authors selected DenseNet after evaluating seven pre-trained models, achieving a baseline validation accuracy of 68%. Following parameter tuning, the optimized DenseNet model reached a validation accuracy of 79%. Notably, the dataset used in this study does not contain distinct food types but rather includes more specific food components, eggs, carrots, and butter, leading to significant visual differences between classes, which simplifies classification. In contrast, my dataset focuses solely on meals that exhibit considerable similarities, making the classification process more challenging.

As the demand for intelligent food recognition systems grows, the integration of advanced machine learning techniques will be crucial. The ongoing developments in this field promise to revolutionize how I interact with food through digital mediums, making technology an indispensable part of culinary experiences and dietary management.

CNNs excel in image processing tasks, making them a popular choice for object classification. Their architecture allows for the efficient categorization of hundreds of distinct classes. Building on the success of CNNs, transformers present a more recent advancement in deep learning. Initially designed for natural language processing, transformers have been adapted for image recognition. Their ability to handle sequential data and focus on relationships between different parts of the data makes them exceptionally effective. Unlike CNNs, which process data in a hierarchical manner, transformers process all parts of the data simultaneously, providing a more comprehensive understanding of the image content. This makes transformers particularly useful for complex image recognition tasks where context and relation between different image parts are crucial (Alp and Şenlik, 2023).

ViT is a pioneering approach that applies the principles of transformers, originally designed for natural language processing, to the domain of image recognition. Unlike traditional convolutional neural networks (CNNs) that process images through localized filters, ViT treats an image as a sequence of fixed-size patches, much like words in a sentence. Each patch is embedded and then processed through a series of transformer blocks that utilize self-attention mechanisms.

This architecture enables the model to capture global dependencies between any parts of the image, which is beneficial for understanding complex scenes where contextual awareness is key. For example, in tasks like object detection or scene segmentation, ViT can leverage its global perspective to better differentiate and classify various elements within the image. Its ability to process all parts of the image simultaneously allows for a more comprehensive understanding of the entire scene, making it particularly useful for image recognition tasks that require a deep understanding of hierarchical and relational context.

Moreover, ViT has shown impressive performance on benchmarks, often surpassing traditional CNNs, especially when trained on large-scale datasets (Akan et al., 2023; Alp et al., 2024). This performance gain underscores the potential of transformer models to reshape the landscape of computer vision by providing a powerful alternative to established convolutional architectures.

Recent research has emphasized the use of ViTs and domain adaptation techniques to improve the accuracy and efficiency of food recognition systems.

Gao and et. al (2024) introduces AlsmViT, a Vision Transformer (ViT)-based method for food image classification, designed to handle visually similar foods. The model incorporates data augmentation (Augmentplus), deeper image processing (LayerScale), and enhanced feature extraction (MLP-GC). Tested on the Food-101 and Vireo Food-172 datasets, the AlsmViT-L model achieved validation accuracies of 95.17% and 94.29%, respectively. But its drawbacks include a relatively large number of model parameters, high computational demands, and significant peak memory usage.

Nijhawan et al. (2024) proposes a hybrid Vision Transformer (ViT) model for food cuisine detection, combining deep learning with hand-crafted features like GIST, HoG, and LBP. Using a dataset of 13 food categories, the model achieved 94.63% accuracy, 95.23% specificity, and 84.42% sensitivity, outperforming CNN-based models. By processing complete image data, it captures finer details, improving classification accuracy. However, the approach's computational cost is high due to the large number of tokens required.

While these models have an end-to-end architecture with a large number of trainable parameters, making the training process more costly, my proposed hybrid method utilizes a pretrained ViT network solely for deep feature extraction, resulting in no trainable parameters in that part of the model; the only trainable component is the classifier, which employs a Random Forest (RF) classifier, making the training process much faster and more cost-effective. These additions offer a more comprehensive view of the current research landscape

and position my contributions within the existing body of knowledge.

This study makes several important contributions to the field of food category recognition. Firstly, the study introduces a novel hybrid approach that combines a pre-trained ViT for feature extraction with a RF classifier. The classification performance of this hybrid method is better than that of traditional end-to-end CNN architecture. It also offers advantages such as efficient training, reduced computational costs, and faster training times, as it restricts the number of trainable parameters to only the classifier. Besides that, the study carefully compares how well the ViT-RF hybrid model works with three well-tuned CNN-based models, which are EfficientNetV2M, ResNet101, and VGG16. Lastly, this research is among the first to evaluate ViT-Based model on the TurkishFoods-15 dataset, contributing to the dataset's benchmark and providing a reliable comparison for future studies in the domain.

2. Materials and Methods

EfficientNetV2M, ResNet101, and VGG16 are deep convolutional neural network architectures that are frequently employed in image classification tasks. EfficientNetV2M (Tan and Le, 2021), the most recent member of the EfficientNet (Tan and Le, 2019) family, attempts to maintain a balance between the performance and the size of the model by scaling the network architecture. ResNet101, an extension of the ResNet (He et al., 2016) family, utilizes residual connections to resolve the vanishing gradient issue and facilitates the training of neural networks that are exceedingly deep. Conversely, VGG16 (Simonyan and Zisserman, 2015) is distinguished by its simplicity, which is characterized by the use of smaller convolutional filters and deeper network layers. In contrast to these CNN models, the ViT (Dosovitskiy et al., 2021) approaches image recognition from a different angle. It leverages self-attention mechanisms typical of transformers used in natural language processing, treating image patches as sequences. This method allows ViT to focus on global dependencies between patches, making it highly effective for tasks requiring the recognition of complex patterns and details in large-scale images.

In the course of our investigation, I implemented fine-tuning on these three models. First, I eliminated the top layer from each model, as it was originally designed for the ImageNet dataset. I customized the models to correspond with the classification of food images by incorporating three additional layers. An AveragePooling2D layer was introduced as the initial step to perform spatial pooling and reduce the spatial dimensions of the features. A Flatten layer was then implemented to transform the pooled features into a vector representation. Subsequently, a Dense layer with ReLU activation was implemented to incorporate non-linearity and to capture intricate relationships within the data. The implementation of a dropout layer with a rate of 0.5 was necessary to prevent overfitting. In order to produce class probabilities for each food image, a Dense layer with SoftMax activation was incorporated as the final output layer (Table 1).

By adding more layers to the pre-trained networks, I was able to better adapt them to our particular food image classification task. Updating the weights of the new layers and freezing the weights of the previous layers was necessary to maintain the learned features during this process. I sought to optimize the classification performance of the models on our food images dataset by leveraging their pre-trained knowledge. Specifically, Table1 contains the parameters of the base-line and fine-tuned models, and the Table 2 contains the compile settings of the model respectively.

Table 1. Transfer learning models parameters

Base-Model	Total Parameters	Trainable Parameters	Non-trainable Parameters
EfficientNetV2M	53,174,723	21,775	53,152,948
ResNet101	43,186,575	528,399	42,658,176
VGG16	14,849,871	135,183	14,714,688
ViT-Base	86,389,248	-	-

Table 2. Model compile parameters

Parameter	Values
Image size	224×224
Batch size	128
Optimization	Adam (learning rate=0.001)
Loss function	Categorical Cross entropy
Epochs	100
Metrics	Categorical Accuracy
Call back	Save best Only

In addition to fine-tuning the convolutional neural network architectures, I also explored the utilization of the ViT for our classification tasks. The pretrained ViT model was used for extracting features, which encapsulate rich contextual and textural information crucial for distinguishing between various food items. These extracted features were then used as inputs for a RF classifier. The choice of RF was based on its ability to handle high-dimensional feature spaces and its strong classification performance, particularly when combined with ViT's extracted features. Its ensemble approach aggregates predictions from multiple decision trees, reducing overfitting and improving prediction accuracy. While alternative classifiers like SVM and KNN were considered, initial tests showed RF to be the best performer on this dataset.

This hybrid approach leverages the deep learning capabilities of ViT in feature extraction with the machine learning efficiency of Random Forest in classification, aiming to enhance the overall accuracy and reliability of the system.

For this study, I utilized the "TurkishFoods-15" (Güngör et al., 2017) dataset, specifically developed to address the underrepresentation of Turkish dishes in existing food recognition datasets. Compiled by researchers from Hacettepe University, this benchmark dataset encompasses images of fifteen popular Turkish meals, with each class containing approximately 500 images. The dataset was primarily sourced from Google Images, following specific search queries to ensure relevance and variety.

The dataset was specifically selected for its comprehensive coverage of diverse food categories relevant to the study. Detailed information about the dataset, including the number of instances, categories, and features, is provided in Table 3.

The images underwent a rigorous cleaning process to eliminate irrelevant content, thereby ensuring the dataset's quality and applicability for training deep learning models. This dataset's creation aimed to provide a comprehensive resource for training and evaluating food recognition systems, particularly those aimed at recognizing Turkish cuisine.

Table 3. Overview of the Turkish foods-15 Dataset: number of instances, categories, and features

Food Name	# images in train	# images in test	# images
Biber dolmasi	436	48	485
Borek	686	76	762
Cig kofte	295	33	328
Enginar	411	46	457
Hamsi	303	34	337
Unkar begendi	283	32	315
icli_kofte	464	52	516
Ispanak	245	27	272
Kebap	784	87	871
Kisir	450	50	500
Kuru fasulye	434	48	482
Lokum	615	68	683
Manti	380	42	422
Simit	429	48	477
Yaprak sarma	454	50	504

3. Results and Discussions

Our experiments were conducted on a system equipped with an Intel(R) Core(TM) i5-7400 CPU, operating at 3.00 GHz, and paired with 8 GB of RAM. For graphical processing, the system was outfitted with an NVIDIA GeForce RTX 2080 GPU.

The food image classification task was used to assess the performance of our fine-tuned models, EfficientNetV2M, ResNet101, and VGG16, alongside ViT. The RGB image dataset, which comprises 15 classes, was utilized to train the models.

To assess the performance of the models, I divided the dataset into training and testing sets using an 80-20 split. This allocation ensures that 80% of the data is used for training the model, while the remaining 20% is reserved for testing to evaluate model accuracy and generalization. Further, to fine-tune and validate our models during the training phase, 20% of the training set was set aside as a validation set. This validation subset allows for the adjustment of model parameters and helps prevent overfitting. This strategy ensures a comprehensive evaluation of the models' performance across unseen data, providing a robust measure of their predictive capabilities.

I removed the top layer from each model during training and added three additional layers: AveragePooling2D, Flatten, and two dense layers. I applied dropout regularization to mitigate overfitting. A categorical cross-entropy loss function was used to train the models, and the Adam optimizer was used to optimize them. I

evaluated all the models on TurkishFoods-15 dataset after training. The evaluation metrics were calculated for each class, as well as the macro average over all classes, and included precision, recall, and F1-score. Table 4 provides a comprehensive comparison of the performance metrics—precision, recall, and F1-score—across four deep learning models (EfficientNetV2M, ResNet101, VGG16, ViT) for the task of recognizing various Turkish dishes.

Vision Transformer (ViT) consistently demonstrates high precision, notably scoring the highest for several dishes like "Biber dolmasi" (0.96), "Enginar" (0.89), and "Kurufasulye" (0.96). EfficientNetV2M also performs well, particularly for "Hamsi" (0.97) and "Ispanak" (0.95). ViT again stands out with exceptional recall scores, especially for "Ispanak" (1.00) and "Simit" (0.98). ResNet101 shows strong recall for "Kisir" (0.98) and "Manti" (0.98). ViT achieves high F1-scores, excelling particularly with "Biber dolmasi" (0.92) and "Kurufasulye" (0.95). EfficientNetV2M and ResNet101 also show competitive F1-scores across several dishes, underscoring their balanced performance. ViT achieves the highest overall accuracy at 0.90, followed closely by EfficientNetV2M and ResNet101 both at 0.87. VGG16 lags slightly at 0.76. ViT leads in macro average F1-scores at 0.91, demonstrating its effectiveness across classes irrespective of class imbalance. In weighted average, ViT also tops the chart at 0.89, followed by EfficientNetV2M and ResNet101 at 0.87.

These results indicate that the Vision Transformer not only excels in individual categories but also maintains superior performance across the board, making it particularly effective for tasks requiring high precision and recall in image classification. EfficientNetV2M and ResNet101 also show robust performance, making them suitable alternatives depending on specific requirements like computational efficiency or model size. VGG16, while slightly less competitive, still offers reasonable accuracy for certain applications. Moreover, Table 5 show the confusion matrixes of all models.

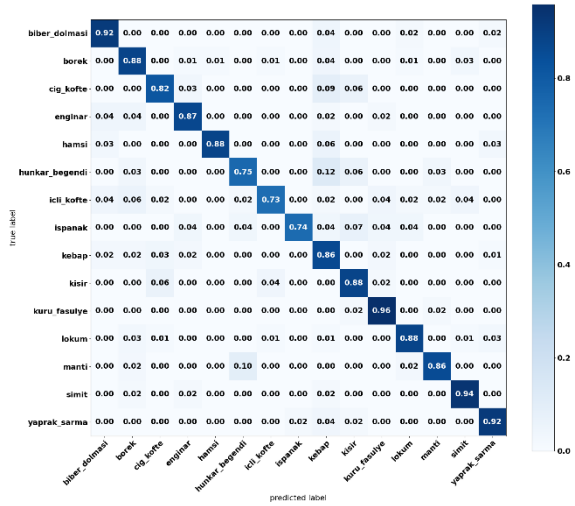
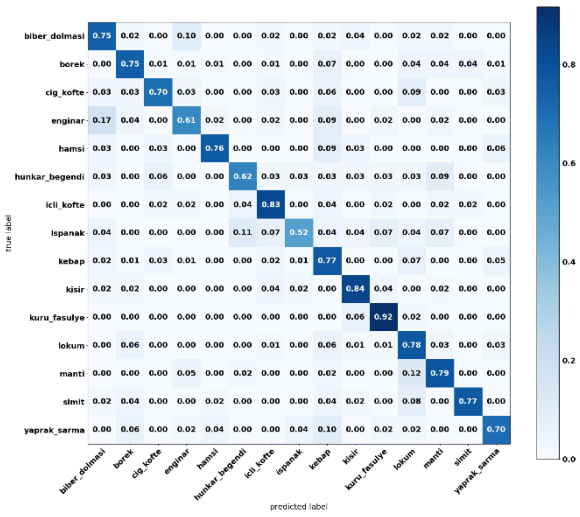
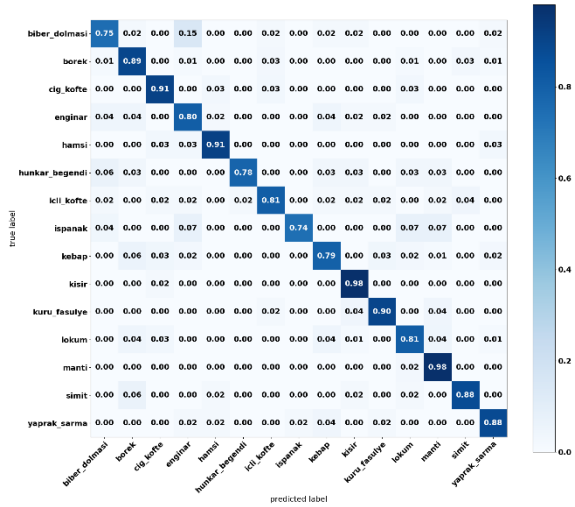
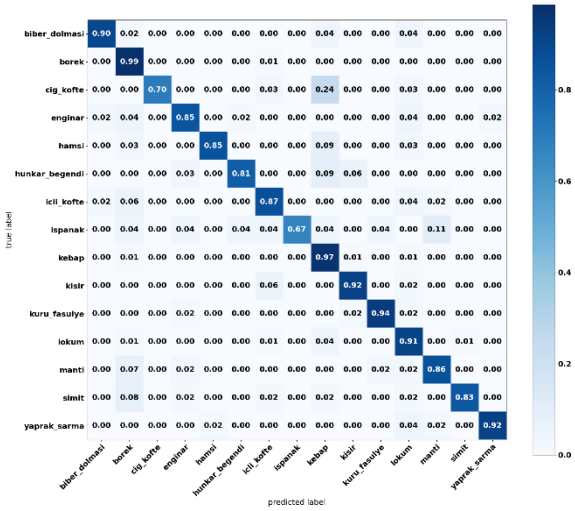
The confusion matrix for EfficientNetV2M shows high diagonal values indicating strong class-specific accuracy for most dishes, with notable performance for "biber_dolmasi" (0.92), "enginar" (0.87), and "kurufasulye" (0.88). These results suggest that EfficientNetV2M is quite effective in distinguishing between different Turkish foods, possibly due to its balanced scaling of depth, width, and resolution which enhances feature extraction across diverse image types.

VGG16, known for its deep architecture and small convolutional filters, also performs well, particularly for "borek" (0.89) and "cig_kofte" (0.91). However, it shows some confusion in classes like "enginar" and "hamsi," possibly due to the simpler and more uniform textures of these foods that challenge the model's deeper and narrower filters.

Table 4. The precision, recall, and F1-score for each class and the macro average were calculated

Food Name	Precision				Recall				f1-score				Support
	EfNetV2M	ResNet101	VGG16	ViT	EfNetV2M	ResNet101	VGG16	ViT	EfNetV2M	ResNet101	VGG16	ViT	48
Biber dolmasi	0.86	0.84	0.69	0.96	0.92	0.75	0.75	0.90	0.89	0.79	0.72	0.92	76
Borek	0.85	0.82	0.79	0.82	0.88	0.89	0.75	0.99	0.86	0.86	0.77	0.89	33
Cig kofte	0.77	0.79	0.74	1.00	0.82	0.91	0.70	0.70	0.79	0.85	0.72	0.82	46
Enginar	0.87	0.71	0.70	0.89	0.87	0.80	0.61	0.85	0.87	0.76	0.65	0.87	34
Hamsi	0.97	0.89	0.84	0.97	0.88	0.91	0.76	0.85	0.92	0.90	0.80	0.91	32
Unkar begendi	0.80	0.96	0.77	0.93	0.75	0.78	0.62	0.81	0.77	0.86	0.69	0.87	52
icli_kofte	0.90	0.89	0.78	0.85	0.73	0.81	0.83	0.87	0.81	0.85	0.80	0.86	27
Ispanak	0.95	0.95	0.74	1.00	0.74	0.74	0.52	0.67	0.83	0.83	0.61	0.80	87
Kebap	0.78	0.87	0.68	0.80	0.86	0.79	0.77	0.97	0.82	0.83	0.72	0.88	50
Kisir	0.85	0.86	0.81	0.92	0.88	0.98	0.84	0.92	0.86	0.92	0.82	0.92	48
Kuru fasulye	0.87	0.88	0.83	0.96	0.96	0.90	0.92	0.94	0.91	0.89	0.87	0.95	68
Lokum	0.92	0.86	0.67	0.81	0.88	0.81	0.78	0.91	0.90	0.83	0.72	0.86	42
Manti	0.92	0.80	0.70	0.88	0.86	0.98	0.79	0.86	0.89	0.88	0.74	0.87	48
Simit	0.90	0.91	0.90	0.98	0.94	0.88	0.77	0.83	0.92	0.89	0.83	0.90	50
Yaprak sarma	0.90	0.88	0.78	0.98	0.92	0.88	0.70	0.92	0.91	0.88	0.74	0.95	48
Accuracy	-	-	-	-	-	-	-	-	0.87	0.85	0.75	0.89	741
Macro avg	0.87	0.86	0.76	0.91	0.86	0.85	0.74	0.86	0.86	0.85	0.75	0.88	741
Weighted avg	0.87	0.86	0.76	0.90	0.87	0.85	0.75	0.89	0.87	0.85	0.75	0.89	741

Table 5. Models' confusion matrices

EfficientNetV2M	*VGG16*
	
ResNet101	*ViT + RF*
	

ResNet101 exhibits strong performance across several food classes with top accuracies for "kurufasulye" (0.92) and "mantı" (0.98). The use of residual connections likely helps it maintain performance across deeper layers, improving the model's ability to learn from complex, varied food images. It also appears to handle intra-class variation effectively, likely due to its ability to leverage residual learning to avoid the vanishing gradient problem.

The Vision Transformer shows excellent performance, especially for "borek" (0.99) and "cig_kofte" (0.91), demonstrating its capability to handle the relational context within food images effectively. Its architecture, which processes image patches through self-attention mechanisms, seems particularly adept at recognizing patterns and details critical for distinguishing similar food items.

Overall, the ViT and ResNet101 models show the most promising results, suggesting that architectures that can capture both long-range dependencies (ViT) and deep residual features (ResNet101) are beneficial for food image classification tasks involving complex and visually diverse dishes like those found in Turkish cuisine. EfficientNetV2M, while slightly less accurate in some classes, still performs robustly, suggesting its utility in scenarios where model scalability is crucial. VGG16, despite being an older model, holds up reasonably well, particularly in less complex food classes, highlighting its continued relevance in image classification tasks.

4. Conclusion

This study examined the effectiveness of transfer learning approaches for categorizing Turkish cuisine images. I aimed to tackle the underrepresentation of Turkish dishes in existing food recognition datasets by fine-tuning CNN architectures, such as EfficientNetV2M, ResNet101, and VGG16, and using the pre-trained ViT for feature extraction and classification with a Random Forest algorithm.

Results showed that the combination of pre-trained ViT and RF outperforms CNNs in terms of accuracy precision, recall, and F1-score.

This combined method made good use of capacity of ViT to detect global dependencies in images, which made it adept at identifying Turkish cuisine's intricate patterns. Moreover, EfficientNetV2M and ResNet101 showed strong performance, making them good options for Turkish cuisine classification. Although VGG16 was not quite as good as the other models, it was still quite accurate, indicating that it is still useful for image classification tasks.

In particular, for diverse and culturally significant cuisines such as Turkish dishes, this study shows the potential of advanced deep learning and transformer-based models to improve food recognition systems. Expanding the dataset and looking into other deep learning architectures could be the focus of future research that aims to make classification more accurate and faster in real-world situations.

One major limitation is that ViT models require large datasets and are computationally expensive, even though I only used them for feature extraction. This can make the approach less suitable for smaller datasets or low-resource environments. Additionally, while efficient, the RF classifier may not always generalize well to highly diverse datasets. In future work, I will explore using state-of-the-art ViT-based and CNN-based models for feature extraction, combined with multiple instance learning as the classifier, to improve performance and generalization. Testing on larger, more diverse datasets will also help enhance scalability and robustness.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	S.A.
C	100
D	100
S	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans. The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to.

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ON THE GENERALIZED WEIGHTED STATISTICAL CONVERGENCE

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Abstract: Statistical convergence and summability represent a significant generalization of traditional convergence for sequences of real or complex values, allowing for a broader interpretation of convergence phenomena. This concept has been extensively examined by numerous researchers using various mathematical tools and applied to different mathematical structures over time, revealing its relevance across multiple disciplines. In the present study, a generalized definition of the concepts of statistical convergence and summability, termed $(\Delta_v^m)_u$ −generalized weighted statistical convergence and $(\Delta_v^m)_u$ −generalized weighted by $[\overline{N}_t]$ −summability for real sequences, is introduced using the weighted density and generalized difference operator. Based on this definition, several fundamental properties and inclusion results, obtained by differentiating the components used in the definitions, are provided.

Keywords: Generalized difference sequence, Weighted density, Weighted statistical convergence, Weighted summability

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1. Introduction

The mathematical structure defines different types of convergence. Convergence types defined on the same structure can also be compared. One of the most recently studied types of convergence is statistical convergence. This form of convergence was initially proposed by Fast (1951) and Steinhaus (1951), and subsequently developed by Schoenberg (1959) to extend the standard topological convergence of real sequences. Salat (1980), Fridy (1985) and Connor (1988) gave remarkable properties of the statistical convergence of real sequences. Afterward, it has been discussed and generalized from many different perspectives or in many different mathematical structures . For instance, we refer the reader for weighted statistical convergence or statistical convergence by using the difference operator (Et and Nuray, 2001; Güngör and Et, 2003; Karakaya and Chishti, 2009; Mursaleen et al. 2012; Belen and Mohiuddine, 2013; Kadak, 2016; Ghosal, 2016; Braha et al., 2021; Et et al., 2021; Kandemir et al., 2023).

In this research, we investigate a generalization of statistical convergence by incorporating the difference operator outlined in (Et and Esi, 2000) along with a sequence of multipliers. Our motivation in this investigation is grounded in the findings of previous studies, specifically studies (Ghossal, 2016; Kandemir et al., 2023).

2. Materials and Methods

The basic tool used in statistical convergence is the concept of asymptotic (natural) density and it is defined for a set $A \subseteq \mathbb{N}^+$ as $\delta(A) = \lim_{n\to\infty} \frac{1}{n} |\{a \leq n: a \in A\}|$. Here, the vertical bars show how many elements are included in the enclosed set. Moreover, $\delta(A) = 0$ for the finite set A, $\delta(\mathbb{N} \setminus A) = 1 - \delta(A)$ and $\delta(A) \leq \delta(B)$ whenever $A \subseteq B$.

Definition 2.1. A real sequence $x = (x_n)$ is called statistical converges to γ if for every $\varepsilon > 0$ the set $\{k \leq n: |x_k - \gamma| \geq \varepsilon\}$ has a natural density of zero, i.e.

$$\lim_{n\to\infty} \frac{1}{n} |\{k \leq n: |x_k - \gamma| \geq \varepsilon\}| = 0.$$

Therefore, the element γ is referred to as the statistical limit of (x_n) and is represented as $st - \lim_{n\to\infty} x_n = \gamma$. S represents all statistically convergent sequences (Fast, 1951).

In order to extend the notion of statistical convergence, researchers have explored various generalizations of the concept of asymptotic density. One such generalization is referred to as weighted density. Let (q_n) be a sequence in $\mathbb{R}^+ \cup \{0\}$ such that $\liminf q_n > 0$ and $\lim Q_n = \infty$, where $Q_n = q_1 + q_2 + \ldots + q_n$ for all $n \in \mathbb{N}$. Accordingly, the weighted density is defined for a set $A \subseteq \mathbb{N}^+$ as

$$\delta_w(A) = \lim_{n\to\infty} \frac{1}{Q_n} |\{a \leq Q_n: a \in A\}|.$$

Similarly, $\delta_w(A) = 0$ for the finite set A, $\delta_w(\mathbb{N} \setminus A) = 1 -$

$\delta_w(A)$ and $\delta_w(A) \leq \delta_w(B)$ whenever $A \subseteq B$. The concept of weighted statistical convergence, first proposed by Karakaya and Chisti (2009) and subsequently refined by Mursaleen et al. (2012), is defined through the use of weighted density as follows.

Definition 2.2. A real sequence $x = (x_n)$ is called weighted statistical converges to γ if, for every $\varepsilon > 0$, $\delta_w(\{k \leq Q_n : q_k|x_k - \gamma| \geq \varepsilon\}) = 0$ holds.

Hence, the element γ is called weighted statistical limit of (x_n) and it is denoted by $S_{\overline{N}} - \lim x = \gamma$. The set of all weighted statistically convergent sequences is denoted by $S_{\overline{N}}$ (Mursaleen et al., 2012).

Also, as a generalization, Ghosal (2016) introduced the notion of weighted statistical convergence of order $\alpha \in (0,1]$.

A sequence space is defined as a linear subspace of the space $\mathbb{R}^{\mathbb{N}}$, which is denoted w. The classical sequence spaces ℓ_∞, c, c_0, ℓ_p with $1 < p < \infty$ are all bounded, convergent, null and p-absolutely summable sequences, respectively. One method for creating new sequence spaces is through the use of the difference operator, defined as $\Delta x_k = x_k - x_{k+1}$. The difference sequence spaces $\lambda(\Delta) = \{(x_k) \in w : \Delta(x_k) \in \lambda\}$ where λ is any of the classical sequence spaces. This concept was first introduced by Kızmaz (1981). Following this, quite a lot of work was done with some generalizations by using the difference operator in some way. One such example is the different sequence spaces of a positive integer order m, $\lambda(\Delta^m) = \{(x_k) \in w : \Delta^m(x_k) \in \lambda\}$ for $m \in \mathbb{N}$ where $\Delta^0 x_k = x_k$ and $\Delta^m x_k = \Delta^{m-1}x_k - \Delta^{m-1}x_{k+1}$ (Et and Çolak, 1995). Clearly, $\Delta^m x_k = \sum_{i=0}^{m} (-1)^i \binom{m}{i} x_{k+i}$ holds. Subsequently, Et and Esi (2000) were expanded in the following manner:

$$\lambda(\Delta_v^m) = \{x = (x_k) : (\Delta_v^m x_k) \in \lambda\}$$

where $(\Delta_v^m x_k) = (\Delta_v^{m-1}x_k - \Delta_v^{m-1}x_{k+1})$ for any fixed sequence of nonzero complex numbers $v = (v_k)$ such that

$$\Delta_v^m x_k = \sum_{i=0}^{m} (-1)^i \binom{m}{i} v_{k+i} x_{k+i}.$$

There is considerable literature on difference sequence spaces by choosing different classical sequence spaces of λ for either case where α is integer or fractional. For instance, we refer the reader to the difference operator (Et and Çolak, 1995; Et and Esi, 2000; Bektas and Çolak, 2005; Barlak 2020).

Among the studies conducted for the purpose of generalizing of statistical convergence, there are studies utilizing the difference operator. Recently, Kandemir et al. (2023) introduced the concept of Δ^m-weighted statistical convergence and Δ^m-weighted $(\overline{N}, Q_n)$ − summability. A real sequence $x = (x_n)$ is referred Δ^m−weighted statistical convergent of order $\alpha \in (0,1]$ (or $S_{\overline{N_t}}(\Delta^m)$ −convergent) to γ if, for every $\varepsilon > 0$,

$$\lim_{n\to\infty} \frac{1}{Q_n^\alpha} |\{k \leq Q_n : q_k|\Delta^m x_k - \gamma| \geq \varepsilon\}| = 0.$$

Hence, it is denoted by $S_{\overline{N_t}} - \lim x = \gamma$. The notation $S_{\overline{N_t}}^{\alpha}(\Delta^m)$ represents the set of all Δ^m-weighted statistically convergent sequences of order α. In this context, the forms of statistical convergence presented in studies Karakaya and Christi (2009) and Mursaleen et al. (2012) are obtained through a specific choice of values for m and α (see Remark 2.1, Kandemir et al. (2023)).

3. Results and Discussion

This section introduces the concepts of $(\Delta_v^m)_u$-generalized weighted statistical convergence and $(\Delta_v^m)_u$-generalized weighted $(\overline{N}, q_n)$-summability and establish the relations between them. In the results and proofs provided, u and t will be defined as follows and will not be redefined each time for the sake of simplicity:

1. U refers to the set of all real sequences $u = (u_k)$ such that $u_k \neq 0$ for all $k \in \mathbb{N}^+$.
2. $q = (q_n)$ is a sequence in $\mathbb{R}^+ \cup \{0\}$ such that $\liminf q_n > 0$ and $\lim_{n\to\infty} Q_n = \infty$ where $Q_n = t_1 + t_2 + \ldots + q_n$ for all $n \in \mathbb{N}$.

Definition 3.1. A sequence $x = (x_n)$ *is said to be* $(\Delta_v^m)_u$ −generalized weighted statistically convergent (or $S_{\overline{N_t}}(\Delta_v^m)_u$-convergent) to γ if for every $\varepsilon > 0$

$$\delta_w(\{k \leq Q_n : q_k|u_k\, \Delta_v^m\, x_k - \gamma| \geq \varepsilon\}) = \lim_{n\to\infty} \frac{1}{Q_n} |\{k \leq Q_n : q_k|u_k\, \Delta_v^m\, x_k - \gamma| \geq \varepsilon\}| = 0.$$

In this way, we express $S_{\overline{N_t}}(\Delta_v^m)_u - \lim x = \gamma$ or $x_k \to \gamma (S_{\overline{N_t}}(\Delta_v^m)_u)$. We use the notation $S_{\overline{N_t}}(\Delta_v^m)_u$ to represent the set of all $(\Delta_v^m)_u$-generalized weighted statistically convergent sequences.

Definition 3.2. Assume that $r > 0$ is a real number and $q_1 > 0$. A sequence $x = (x_n)$ is $(\Delta_v^m)_u$ −generalized weighted $\left[\overline{N_t}\right]$ −summable (or $[\overline{N_t}, (\Delta_v^m)_u]_r$ − summable) to γ provided that

$$\lim_{n\to\infty} \frac{1}{Q_n} \sum_{k=0}^{n} q_k|u_k\, \Delta_v^m\, x_k - \gamma|^r = 0.$$

In this way, we express $[\overline{N_t}, (\Delta_v^m)_u]_r - \lim x = \gamma$ or $x_n \to \gamma [\overline{N_t}, (\Delta_v^m)_u]_r$. We denote the set of all $(\Delta_v^m)_u$ −generalized weighted $\left[\overline{N_t}\right]$ − summable sequences by $[\overline{N_t}, (\Delta_v^m)_u]_r$.

Remark 3.3. In consideration of Definitions 2.1 and 2.2, it is evident the following situations are observed:

1. $S_{\overline{N_t}}(\Delta_v^m)_u = S$ if $m = 0$ and $u_k = v_k = q_k = 1$ for all $k \in \mathbb{N}$ (Fast, 1951).
2. $S_{\overline{N_t}}(\Delta_v^m)_u = S_{\overline{N}}(\Delta_v)$ and $[\overline{N_t}, (\Delta_v^m)_u]_r = [\overline{N}, q_n]_r$ if $m = 0$ and $u_k = v_k = 1$ for all $k \in \mathbb{N}$ (Karakaya, 2009; Mursaleen et all. (2012)).
3. $S_{\overline{N_t}}(\Delta_v^m)_u = S_{\overline{N_t}}(\Delta^m)$ and $[\overline{N_t}, (\Delta_v^m)_u]_r = [\overline{N_t}](\Delta^m, r)$ if $\alpha = 1$ and $u_k = v_k = 1$ for all $k \in \mathbb{N}$ (Kandemir et al., 2023).

Theorem 3.4. Assume that $x = (x_k) \in \overline{N_t}, (\Delta_v^m)_u]_r$ *and*

$[\overline{N_t}, (\Delta_v^m)_u]_r - limx = \gamma$. *Then* x *is* $S_{\overline{N_t}}(\Delta_v^m)_u$ −statistically converges to γ, if one of the following two conditions holds:

1. $r \in (0,1)$ and $0 \le |u_k\ \Delta_v^m\ x_k - \gamma| < 1$ for every k,
2. $r \in [1,\infty)$ and $1 \le |u_k\ \Delta_v^m\ x_k - \gamma| < \infty$ for every k.

Proof. Since the sequence $x = (x_k)$ is $[\overline{N_t}, (\Delta_v^m)_u]_r$ −summable to γ we see that

$$\lim_{n\to\infty} \frac{1}{Q_n} \sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r = 0.$$

If both (1) and (2) are satisfied, it can be seen that for every k,

$$q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \ge q_k |u_k\ \Delta_v^m\ x_k - \gamma|$$

holds. Then we obtain, for any $\varepsilon > 0$,

$$\begin{aligned}
&\sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \\
&\ge \sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma| \\
&\ge \sum_{k\in\{k\le Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \ge \varepsilon\}}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma| \\
&\ge \sum_{k\in\{k\le Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \ge \varepsilon\}}^{n} \varepsilon \\
&\ge |\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma| \ge \varepsilon\}|\ \varepsilon
\end{aligned}$$

and this implies

$$\varepsilon \delta_w(\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma| \ge \varepsilon\}) \le \frac{1}{Q_n} \sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r.$$

Taking limit as $n \to \infty$, this means $\delta_w(\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma| \ge \varepsilon\}) = 0$, so that $x \in S_{\overline{N_t}}(\Delta_v^m)_u$.

Theorem 3.5. Suppose that the sequence $x = (x_k)$, $S_{\overline{N_t}}(\Delta_v^m)_u$ −converges to γ and for every $k \in \mathbb{N}$, $q_k |u_k\ \Delta_v^m\ x_k - \gamma| \le M$ for some $M > 0$. Then (x_n) *is* $[(\overline{N}, q_n), (\Delta_v^m)_u]_r$ −summable to γ, if one of the following two conditions holds:

1. $r \in (0,1)$ and $1 \le M < \infty$,
2. $r \in [1,\infty)$ and $0 \le M < 1$.

Proof. If x, $S_{\overline{N_t}}(\Delta_v^m)_u$ −statistically converges to γ then for every $\varepsilon > 0$ we have $\delta_w(K_{Q_n}(\varepsilon)) = 0$ where $K_{Q_n}(\varepsilon) = \{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma| \ge \varepsilon\}$. If both 1 and 2 are satisfied, it can be seen that for every $k \in \mathbb{N}$,

$$q_k |u_k\ \Delta_v^m\ x_k - \gamma| \le M$$

holds. Then, for every $\varepsilon > 0$, we obtain

$$\begin{aligned}
&\sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \\
&= \sum_{k\notin\{k\le Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \ge \varepsilon\}}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \\
&+ \sum_{k\in\{k\le Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \ge \varepsilon\}}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \\
&\le \varepsilon^r Q_n + M |\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma| \ge \varepsilon\}|.
\end{aligned}$$

That is, for every $\varepsilon > 0$

$$\begin{aligned}
&\frac{1}{Q_n} \sum_{k=1}^{n} q_k |u_k\ \Delta_v^m\ x_k - \gamma|^r \\
&\le \varepsilon^r + M \delta_w(K_{Q_n}(\varepsilon))
\end{aligned}$$

holds. As a result, we deduce x, $[\overline{N_t}, (\Delta_v^m)_u]_r$ −summable to γ.

Theorem 3.6. $(\Delta_v^m)_u$- generalized weighted statistically convergent sequence $x = (x_k)$ has a unique $(\Delta_v^m)_u$ −limit.

Proof. Suppose that $S_{\overline{N_t}}(\Delta_v^m)_u - \lim x = \gamma_1$, $S_{\overline{N_t}}(\Delta_v^m)_u - \lim x = \gamma_2$ and $\gamma_1 \ne \gamma_2$ hold. Choose $\varepsilon, \delta \in \mathbb{R}^+$ such that $\varepsilon = \frac{1}{2}|\gamma_1 - \gamma_2|$ and $\liminf q_k > \delta > 0$. Hence, the following inequality holds:

$$\begin{aligned}
&1 \le |\{k \le Q_n : q_k |\gamma_1 - \gamma_2| \ge \varepsilon\delta\}| \\
&\le |\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_1| \ge \varepsilon\delta\}| \\
&+ |\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_2| \ge \varepsilon\delta\}|.
\end{aligned}$$

Consequently, we have

$$\begin{aligned}
1 \le \delta_w(|\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_1| \ge \varepsilon\}|) \\
+ \delta_w(|\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_2| \\
\ge \varepsilon\}|) = 0.
\end{aligned}$$

This contradiction indicates that γ_1 must be equal to γ_2.

Theorem 3.7. $(\Delta_v^m)_u$ −generalized weighted $[\overline{N_t}]$ −summable sequence $x = (x_k)$ has a unique $[\overline{N_t}, (\Delta_v^m)_u]_r$ −limit.

Proof. The proof is identical to that presented above.

Theorem 3.8. *Let* $S_{\overline{N_t}}(\Delta_v^m)_u - limx = \gamma_1$ and $S_{\overline{N_t}}(\Delta_v^m)_u - limy = \gamma_2$. Then

(i) $S_{\overline{N_t}}(\Delta_v^m)_u - \lim(x+y) = \gamma_1 + \gamma_2$.
(ii) $S_{\overline{N_t}}(\Delta_v^m)_u - \lim cx = c\gamma_1$, $c \in \mathbb{R}$.

Proof. For (i), the assertion is obvious from the following inclusion:

$$\begin{aligned}
&\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - (\gamma_1 + \gamma_2)| \ge \varepsilon\} \\
&\subseteq \{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_1| \ge \frac{\varepsilon}{2}\} \\
&\cup \left\{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_2| \ge \frac{\varepsilon}{2}\right\}.
\end{aligned}$$

For (ii), the assertion is clear if $c = 0$. If $c \ne 0$, then proof can be seen from the following equality:

$$\begin{aligned}
&\{k \le Q_n : q_k |u_k\ \Delta_v^m\ (cx_k) - (c\gamma_1)| \ge \varepsilon\} \\
&= \{k \le Q_n : q_k |u_k\ \Delta_v^m\ x_k - \gamma_1| \ge \frac{\varepsilon}{|c|}\}.
\end{aligned}$$

Theorem 3.9. Suppose that $q = (q_n)$ and $s = (s_n)$ be real sequences of nonnegative real numbers such that $liminf q_n > 0$, $liminf s_n > 0$, $\lim_{n\to\infty} Q_n = \infty$, $\lim_{n\to\infty} S_n = \infty$ where $Q_n = t_1 + t_2 + \ldots + q_n$ and $S_n = s_1 + s_2 + \ldots + s_n$ for all $n \in \mathbb{N}$. If ,for all $k \in \mathbb{N}$, $q_k \le s_k$ and $liminf \frac{Q_n}{S_n} > 0$ hold, then the following *inclusions hold:*

$S_{\overline{N_s}}(\Delta_v^m)_u \subseteq S_{\overline{N_t}}(\Delta_v^m)_u$

and

$[\overline{N_s}, (\Delta_v^m)_u]_r \subseteq [\overline{N_t}, (\Delta_v^m)_u]_r$.

Proof. Choose $x = (x_k) \in S_{\overline{N_s}}(\Delta_v^m)_u$ such that $S_{\overline{N_s}}(\Delta_v^m)_u$-$\lim x = \gamma$. For every $\varepsilon > 0$, from the selection of the sequences, it is observed that the following inequality is satisfied:

$$q_k |u_k \Delta_v^m x_k - \gamma| \leq s_k |u_k \Delta_v^m x_k - \gamma|$$

and hence

$$\begin{aligned} &\{k \leq Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\} \\ &\subseteq \{k \leq S_n : s_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}. \end{aligned} \quad (1)$$

Therefore

$$\begin{aligned} &\frac{1}{S_n} |\{k \leq S_n : s_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}| \\ &\geq \frac{1}{S_n} |\{k \leq Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}| \\ &\geq \frac{Q_n}{S_n} \frac{1}{Q_n} |\{k \leq Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}| \end{aligned}$$

holds. Taking limit as $n \to \infty$, since $\liminf \frac{Q_n}{S_n} > 0$ holds, $x \in S_{\overline{N_s}}(\Delta_v^m)_u$ implies $x \in S_{\overline{N_t}}(\Delta_v^m)_u$. The proof for the second inclusion follows a nearly identical process.

Theorem 3.10. Assume that $q = (q_n)$ and $s = (s_n)$ be real sequences of nonnegative real numbers such that $liminf q_n > 0$, $liminf s_n > 0$, $\lim_{n\to\infty} Q_n = \infty$, $\lim_{n\to\infty} S_n = \infty$ where $Q_n = t_1 + t_2 + \ldots + q_n$ and $S_n = s_1 + s_2 + \ldots + s_n$ for all $n \in \mathbb{N}$. If ,for all $k \in \mathbb{N}$, $q_k \leq s_k$ and $limsup \frac{S_n}{Q_n} < \infty$ hold, then the following inclusions hold:

$S_{\overline{N_s}}(\Delta_v^m)_u \subseteq S_{\overline{N_t}}(\Delta_v^m)_u$

and

$[\overline{N_s}, (\Delta_v^m)_u]_r \subseteq \overline{N_t}, (\Delta_v^m)_u]_r$.

Proof. Choose $x = (x_k) \in S_{\overline{N_s}}(\Delta_v^m)_u$ such that $S_{\overline{N_s}}(\Delta_v^m)_u$-$\lim x = \gamma$. According to the conditions of the theorem, the inclusion (1) above is ensured. Hence, we have

$$\begin{aligned} &\frac{1}{Q_n} |\{k \leq Q_n : q_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}| \\ &\leq \frac{1}{Q_n} |\{k \leq S_n : s_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}| \\ &\leq \frac{S_n}{Q_n} \frac{1}{S_n} |\{k \leq S_n : s_k |u_k \Delta_v^m x_k - \gamma| \geq \varepsilon\}|. \end{aligned}$$

Taking limit as $n \to \infty$, since $\limsup \frac{S_n}{Q_n} < \infty$ hold, $x \in S_{\overline{N_s}}(\Delta_v^m)_u$ implies $x \in S_{\overline{N_t}}(\Delta_v^m)_u$. Again, the proof for the second inclusion is similar.

Theorem 3.11. If, for the sequences $u = (u_k) \subset \mathbb{R}^+ \cup \{0\}$ and $w = (w_k) \subset \mathbb{R}^+ \cup \{0\}$, the condition $u_k \leq w_k$ is satisfied for all $k \in \mathbb{N}$, then the following inclusions hold:

$S_{\overline{N_t}}(\Delta_v^m)_u \subseteq S_{\overline{N_t}}(\Delta_v^m)_w$

and

$[\overline{N_s}, (\Delta_v^m)_u]_r \subseteq \overline{N_t}, (\Delta_v^m)_w]_r$.

Theorem 3.12. If, for the sequences $v = (v_k) \subset \mathbb{R}^+ \cup \{0\}$ and $z = (z_k) \subset \mathbb{R}^+ \cup \{0\}$, the condition $v_k \leq z_k$ is satisfied for all $k \in \mathbb{N}$, then the following inclusions hold:

$S_{\overline{N_t}}(\Delta_v^m)_u \subseteq S_{\overline{N_t}}(\Delta_z^m)_u$

and

$[\overline{N_s}, (\Delta_v^m)_u]_r \subseteq \overline{N_t}, (\Delta_z^m)_u]_r$.

4. Conclusion

Numerous convergence concepts have emerged after the advent of the topological convergence concept in classical analysis. Among these, statistical convergence, a generalization of topological convergence, has been the subject of intense study. Initially defined for real series, statistical convergence has been examined and generalized in numerous mathematical structures, with generalizations being made in each case. In this study, we also generalized statistical convergence and summability by using the weighted density, difference operator, and sequences of nonzero real numbers. We presented fundamental results and some relations related to existing literature. Additionally, we presented some inclusion theorems related to weighted statistical convergence and summability concepts. For further study, one can consider analogous results regarding the difference operator with fractional order instead of a positive integer m.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	Ç.A.B.	E.B.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or

humans.

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COMPACT ANALYSIS OF THE NECESSITY OF PADÉ APPROXIMATION FOR DELAYED CONTINUOUS-TIME MODELS IN LQR, H-INFINITY AND ROOT LOCUS CONTROL STRATEGIES

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Abstract: This paper presents a comprehensive analysis of the need for the Padé approximation for continuous-time models with delays, focusing on its critical role in addressing the control challenges posed by time delays. Time delays, often referred to as dead times, transport delays or time lags, are inherent in a wide range of industrial and engineering processes. These delays introduce phase shifts that degrade control performance by reducing control bandwidth and threatening the stability of closed-loop systems. Accurate modelling and compensation of these delays is essential to maintain system stability and ensure effective control. This paper highlights the difficulties that arise when using advanced control techniques such as root locus (RL), linear quadratic regulator (LQR) and H-infinity (H_∞) control in systems with delays. Representing delays in exponential form leads to an infinite number of state problems, complicating the design and analysis of controllers in such systems. To address these challenges, the Padé approximation is proposed as an effective method for approximating time delays with rational polynomials of appropriate order. This approach allows for more accurate simulation, system analysis and controller design, thereby mitigating the problems caused by delays. The paper also provides a detailed comparative analysis between the Padé approximation and Taylor polynomials, demonstrating the superiority of the former in achieving accurate delay modelling and control performance. The results show that the use of Padé approximation not only improves the accuracy of system models, but also improves the robustness and stability of control strategies such as RL, LQR, and H_∞. These results highlight the importance of the Padé approximation as a valuable tool in the design of delay-affected control systems, offering significant advantages for both theoretical and practical applications.

Keywords: Padé approximation, Time delay systems, Continuous-time models, Infinite number of state problem, Rational polynomial approximation, Dead time compensation

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1. Introduction

Time delays, both distorting and non-distorting, are an integral part of many engineering applications, particularly in the design and analysis of advanced control systems (Pujol-Vazquez et al., 2020; Zhang et al., 2020; Zhang et al., 2024). In these systems, delays occur naturally due to physical phenomena, communication delays or processing times, and they significantly complicate both the design and performance of control strategies. Ignoring the effects of these delays can have serious consequences, such as reduced system performance or even instability, since time delays tend to degrade the control process by introducing phase shifts and reducing the control bandwidth (Mondié et al., 2022; Shangguan et al., 2020; Wu et al., 2023). Therefore, the development of appropriate control principles for time-delayed dynamic systems with uncertainties has been an important research topic (Li et al., 2020; Abbasspour et al., 2020; Belhamel et al., 2020).

In classical control theory, root locus (RL) analysis is a widely used graphical method to investigate how the roots of a system change in response to variations in system parameters, in particular the feedback gain (Luyben, 2020; Werth et al., 2020). However, when dealing with delayed systems, RL analysis faces significant challenges. Time delays introduce transcendental terms into the system's transfer function, creating an infinite number of poles. These poles make it virtually impossible to plot the RL diagram and complicate closed loop stability analysis.

In modern control theory, approaches such as linear quadratic regulator (LQR) and H-infinity (H_∞) control are popular because of their ability to optimize system performance and stability while dealing with uncertainties and disturbances (Handaya and Fauziah, 2021; Priyambodo et al., 2020; Menezes and Araújo, 2023; Anh, 2020). LQR seeks to minimize a quadratic cost function while controlling a dynamic system with linear dynamics (Fridovich-Keil et al., 2020; Khamies et al., 2021; Yang et al., 2021). Similarly, H_∞ control focuses

on optimizing system performance by solving a mathematical optimization problem to achieve stability with guaranteed robustness (Yang et al., 2021; Zhou et al., 2020). Despite their wide applicability and advantages such as optimality, computational efficiency and robustness - both LQR and H_∞ face significant difficulties when applied to continuous-time systems with delays due to the infinite number of state problems introduced by time delays (Kanokmedhakul et al., 2024). To overcome these challenges, it is essential to convert the time delay term into a rational function form, which simplifies the analysis of the system and the design of the controller (De Persis and Tesi, 2021; Chen et al., 2020; Abdullah, 2021; Maghfiroh et al., 2022). The Padé approximation provides a practical solution to this conversion by approximating the time delay as a rational polynomial (Wei et al., 2016; Hu et al., 2024). This method is widely favoured for its flexibility in adjusting accuracy, preserving system dynamics, and ease of implementation. In addition, it significantly improves frequency domain analysis and provides more manageable system representations for control design (Gluzman, 2020).

This paper presents a detailed investigation of the necessity of the Padé approximation for delayed continuous-time models, with a focus on its application to RL, LQR, and H_∞ control strategies. The main contributions of this paper are as follows:

i. The study provides a clear methodology for converting time delays from exponential form to rational polynomials using the Padé approximation, which simplifies the analysis of control systems with delays.

ii. By implementing the Padé approximation, the infinite pole problem in delayed systems is addressed, allowing for more accurate RL analysis and improved system stability when using LQR and H_∞ techniques.

iii. A comprehensive comparison with other polynomial approximations, such as Taylor series, shows that Padé offers superior accuracy and preservation of system behaviour, making it ideal for practical control system design.

iv. The study highlights the relevance of these results in real engineering applications where the use of delayed models is inevitable, providing practical solutions for improving the performance of modern control systems.

2. Materials and Methods

2.1. Padé Approximations of Time Delay

Approximations can be derived by determining the numerator and denominator coefficients and expressing a function as the ratio of two power series, known as a rational polynomial. When functions contain poles, Padé approximations offer a significant advantage over Taylor series and Taylor polynomials, which are among the most commonly used approximation methods. This advantage arises because Padé approximations use rational functions, which allow a more accurate representation of functions with poles than traditional power series expansions (Pinheiro and Colón, 2024).

The Padé approximation $R_{L/M} \equiv [L/M]$ to any power series is given by (equation 1)

$$A(x) = \sum_{j=0}^{\infty} a_j x^j \tag{1}$$

Considering that $A(x)$ is a transcendental function (e.g. e^x), as the time delay approximation is the basis of this study, each term of the expansion of equation 1 is given by the Taylor series about x_0 (equation 2)

$$a_n = \frac{1}{n!} A^{(n)}(x_0) \tag{2}$$

Substituting in equation 2, the coefficients are as follows (equation 3):

$$A(x) - \frac{P_L(x)}{Q_M(x)} = 0 \tag{3}$$

An additional constraint can be enforced since $Q_M(x)$ can be multiplied by any constant, which will rescale the other coefficients. The standard scaling method is defined as $Q_M(0) = 1$. The expansion of equation 3 gives (equations 4 and 5)

$$P_L(x) = p_0 + p_1 x + p_2 x^2 + \cdots p_L x^L \tag{4}$$

$$Q_M(x) = 1 + q_1 x + q_2 x^2 + \cdots q_M x^M \tag{5}$$

The set of equations based on the equations 3-5 are given by (equation 6)

$$\begin{gathered} a_0 = p_0 \\ a_1 + a_0 q_1 = p_1 \\ a_2 + a_1 q_1 + a_0 q_2 = p_2 \\ \vdots \\ a_L + a_{L-1} q_1 + \cdots + a_0 q_L = p_L \\ a_{L+1} + a_L q_1 + \cdots + a_{L-M+1} q_M = 0 \\ \vdots \\ a_{L+M} + a_{L+M-1} q_1 + \cdots + a_L q_M = 0 \end{gathered} \tag{6}$$

where $q_j = 0$ for $j > M$ and $a_n = 0$ for $n < 0$. Directly solving these yields (equation 7):

$$\frac{L}{M} = \frac{\begin{bmatrix} a_{L-m+1} & a_{L-m+2} & \cdots & a_{L+1} \\ \vdots & \vdots & \ddots & a_{L+M} \\ a_L & a_{L+1} & \cdots & a_{L+M} \\ \sum_{j=M}^{L} a_{j-M} x^j & \sum_{j=M-1}^{L} a_{j-M+1} x^j & \cdots & \sum_{j=0}^{L} a_j x^j \end{bmatrix}}{\begin{bmatrix} a_{L-M+1} & a_{L-M+2} & \cdots & a_{L+1} \\ \vdots & \vdots & \ddots & \vdots \\ a_L & a_{L+1} & \cdots & a_{L+M} \\ x^M & x^{M-1} & \cdots & 1 \end{bmatrix}} \tag{7}$$

If the lower index is greater than the upper, the sums are replaced by a zero. Alternative forms are shown as (equations 8 and 9)

$$\frac{L}{M} = \sum_{j=0}^{L-M} a_j x^j + x^{L-M+1} \boldsymbol{w}^{\boldsymbol{T}}{}_{L/M} \, W^{-1}{}_{L/M} \boldsymbol{w}_{L/M} \tag{8}$$

$$\frac{L}{M} = \sum_{j=0}^{L+n} a_j x^j + x^{L+n+1} \boldsymbol{w}^{\boldsymbol{T}}{}_{(L+M)/M} \, W^{-1}{}_{L/M} \boldsymbol{w}_{(L+n)/M} \tag{9}$$

where (equations 10 and 11)

$$W_{L/M} = \begin{bmatrix} a_{L-M+1} - x a_{L-M+2} & \cdots & a_L - x a_{L+1} \\ \vdots & \ddots & \vdots \\ a_L - x a_{L+1} & \cdots & a_{L+M-1} - x a_{L+M} \end{bmatrix} \tag{10}$$

$$\boldsymbol{w}_{L/M} = \begin{bmatrix} a_{L-M+1} \\ a_{L-M+2} \\ \vdots \\ a_L \end{bmatrix} \quad (11)$$

and the relation between n and M satisfies the criterion of $0 \leq n \leq M$. The Padé approximation of e^{-x} with a numerator order $L = 3$ and denominator order $M = 3$ is given in Table 1.

Table 1. Padé approximation of e^{-x} with numerator order $L = 3$ and denominator order $M = 3$

L M	0	1	2	3
0	$\frac{1}{1}$	$\frac{1-x}{1}$	$\frac{1-x+\frac{1}{2}x^2}{1}$	$\frac{1-x+\frac{1}{2}x^2-\frac{1}{6}x^3}{1}$
1	$\frac{1}{1+x}$	$\frac{1-\frac{1}{2}x}{1+\frac{1}{2}x}$	$\frac{1-\frac{2}{3}x+\frac{1}{6}x^2}{1+\frac{1}{3}x}$	$\frac{1-\frac{3}{4}x+\frac{1}{4}x^2-\frac{1}{24}x^3}{1+\frac{1}{4}x^2}$
2	$\frac{1}{1+x+\frac{1}{2}x^2}$	$\frac{1-\frac{1}{3}x}{1+\frac{2}{3}x+\frac{1}{6}x^2}$	$\frac{1-\frac{1}{2}x+\frac{1}{12}x^2}{1+\frac{1}{2}x+\frac{1}{12}x^2}$	$\frac{1-\frac{3}{5}x+\frac{3}{20}x^2-\frac{1}{60}x^3}{1+\frac{2}{5}x+\frac{1}{20}x^2}$
3	$\frac{1}{1+x+\frac{1}{2}x^2+\frac{1}{6}x^3}$	$\frac{1-\frac{1}{4}x}{1+\frac{3}{4}x+\frac{1}{4}x^2+\frac{1}{24}x^3}$	$\frac{1-\frac{2}{5}x+\frac{1}{20}x^2}{1+\frac{3}{5}x+\frac{3}{20}x^2+\frac{1}{60}x^3}$	$\frac{1-\frac{1}{2}x+\frac{1}{10}x^2-\frac{1}{120}x^3}{1+\frac{1}{2}x+\frac{1}{10}x^2+\frac{1}{120}x^3}$

2.2. A Comparative Analysis using Taylor Polynomials

An analogy with the Taylor series expansion of e^{-x} around $x = 0$, as presented in equation 12, helps to highlight the significance of the Padé approximation.

$$e^{-x} = \sum_{n=0}^{\infty} \frac{(-x)^n}{n!} = 1 - x + \frac{1}{2}x^2 - \frac{1}{6}x^3 + \cdots \quad (12)$$

To transform equation 12 into the Padé approximation, the desired order of the rational polynomial - specifically, the choice of numerator and denominator orders as shown in Table 1 - must be determined (Conca et al., 2024). For example, if both the numerator order L and the denominator order M are chosen as first order, the Padé approximation of order M over L is defined by the rational function shown in equation 13.

$$R(x) = \frac{\sum_{j=0}^{M} a_j x^j}{1 + \sum_{k=1}^{L} b_k x^k} \quad (13)$$

Solving equation 13 for the Padé approximation of order 1/1 gives the expression provided in equation 14.

$$R(x) = \frac{\sum_{j=0}^{1} a_j x^j}{1 + \sum_{k=1}^{1} b_k x^k} = \frac{a_0 + a_1 x}{1 + b_1 x} \quad (14)$$

The coefficients a_0, a_1, and a_2 are determined by equating equation 14 to the Taylor polynomial of order $M + L$. Since both the numerator and denominator are of order 1, this corresponds to equating the expression to the second-order Taylor polynomial, as shown in equation 15.

$$R(x) = \frac{a_0 + a_1 x}{1 + b_1 x} = 1 - x + \frac{1}{2}x^2 \quad (15)$$

Extending equation 15 to solve for the coefficients yields the following results:

$$a_0 + a_1 x = 1 - x + \frac{1}{2}x^2 + b_1 x - b_1 x^2 + \frac{1}{2}b_1 x^3 \quad (16)$$

$$a_0 = 1, \qquad a_1 = -\frac{1}{2}, \qquad b_1 = \frac{1}{2} \quad (17)$$

An important aspect to note here is the presence of a residual term in the equation. In this example, when considering up to order $M + L$, the x^3 term is discarded during the process. This distinction highlights a key difference between the Padé approximation and the Taylor polynomial, as the higher-order term is omitted in the Padé approach. By excluding this term, the resulting approximation provides a closer fit to e^{-x} compared to the second-order Taylor polynomial, as demonstrated in Figure 1.

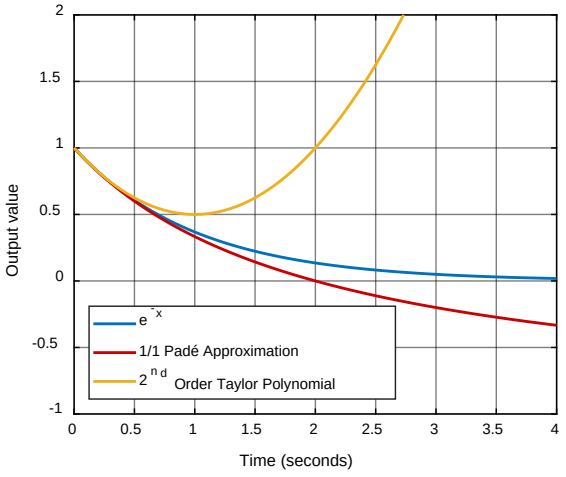

Figure 1. Comparison of the Padé approximation and the second-order Taylor polynomial e^{-x}.

Looking at these results in the context of transfer functions used for mathematical modelling in control systems, it is clear that for the same number of states, a transfer function with both poles and zeros exhibits more

complex behaviour than one with only zeros.

2.3. Determining the Order of Approximation

One of the key considerations in approximation applications is the choice of order for both the numerator and denominator polynomials, particularly when deciding between equal-order and mixed-order approximations. Each of the approximation in Table 1 can be chosen to represent the e^{-x}. A comparison between the 2/2 and 2/3 Padé approximations is shown in Figure 2.

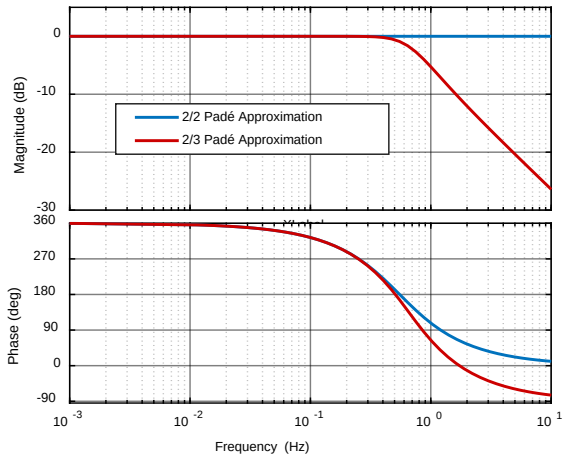

Figure 2. Comparison of 2/2 and 2/3 Padé approximations for e^{-x}.

However, only the equal-order Padé approximations (terms along the diagonal in Table 1) affect the phase without affecting the gain. These approximations behave like all-pass filters, a type of signal processing filter that adjusts the phase relationship between different frequencies while maintaining a uniform gain across all frequencies.

The 2/2 Padé approximation results in a gain of 0 decibels at all frequencies, affecting only the phase of the system, while the gain remains constant. In contrast, the 2/3 approximation shows a drop in gain at higher frequencies. The preference for an all-pass filter is due to the fact that a time delay only affects the phase of a signal without affecting its gain. The choice of the appropriate order of approximation is critical and depends on both the magnitude of the delay and the speed of the system. Figure 3 illustrates a comparison of the step and phase responses between the delay-free approximation and the original time-delayed system.

As shown in Figure 3, higher-order approximations give a closer phase match to the actual function over a wider frequency range. Specifically, the 2/2 approximation is accurate up to approximately 2 rad/sec, the 3/3 approximation up to 4 rad/sec, the 4/4 approximation up to 6 rad/sec, and the 5/5 approximation up to 10 rad/sec. These results highlight that the choice of approximation order should be guided by the critical frequencies of the system. In control system design, the most critical frequency is often the cut-off frequency where the gain falls below -3 dB, as this point has a significant impact on system performance in a closed-loop configuration.

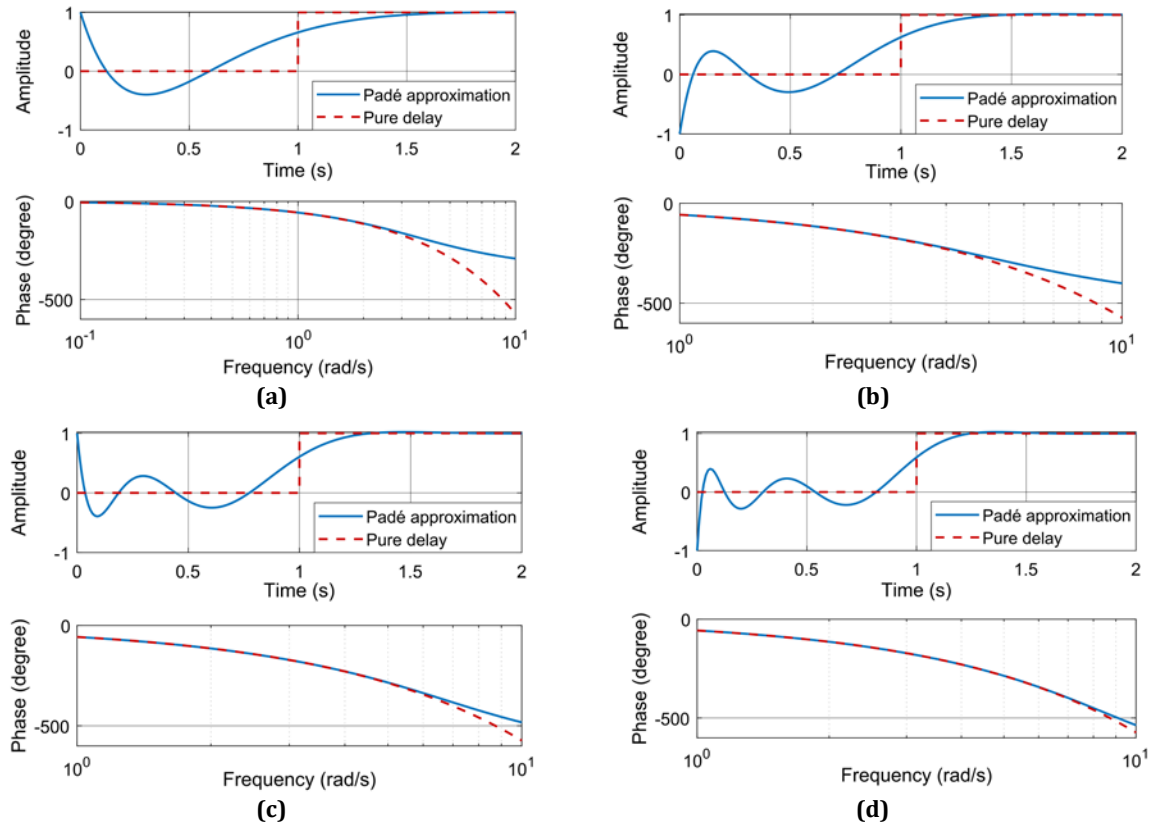

Figure 3. Comparison of the phase response of the Padé approximations: a) 2/2, b) 3/3, c) 4/4, and d) 5/5.

2.4. Time Delay in Control Systems

Dead times, also referred to as time lags or transport delays, are a common feature of processes in feedback control systems. These delays pose significant challenges to control, as they introduce linear phase shifts that reduce the control bandwidth and compromise the stability of the control system. The generic form of the time delay differential equation for $x(t) \in \mathbb{R}^n$ is given as follows:

$$\frac{d}{dt}x(t) = f(t, x(t), x_t) \quad (18)$$

where $x_t = \{x(\tau): \tau \leq t\}$ is the past trajectory of the solution. f acts as a functional operator from $\mathbb{R} \times \mathbb{R}^n \times C^1(\mathbb{R}, \mathbb{R}^n)$ to $\mathbb{R}^n$ in this equation.

Consider a signal $f = x(t)$, which is zero for negative time but undergoes a change at $t = 0$ seconds. The delayed function, $x(t - T)$,, represents this signal being delayed by T seconds. The Laplace transform of such a delayed function is expressed as

$$g(t) = \begin{cases} 0, 0 \leq t \leq T \\ f(t-T), t \geq T \end{cases} \quad (19)$$

$$G(s) = \mathcal{L}\{g(t)\} = \mathcal{L}\{f(t-T)\} = \int_0^\infty e^{-st} g(t) dt \quad (20)$$

$$G(s) = \int_T^\infty e^{-st} f(t-T) dt = \int_0^\infty e^{-s(\tau+T)} f(\tau) d\tau \quad (21)$$

$$G(s) = e^{-sT} F(s) \quad (22)$$

where T, the delay, is expressed in terms of seconds. Thus, an element delaying T seconds has a transfer function of $TF(s) = e^{-sT}$.

3. Results and Discussion

Accurately capturing time delays in system models is essential for reliable simulation, system analysis and effective controller design because delays are inherent in many dynamic systems. Failure to model them properly can lead to performance degradation and inaccurate predictions of system behaviour. Tools such as the Bode plot, widely used in control theory, provide an effective means of analyzing systems with delays, providing valuable insight into frequency response, stability margins and overall system robustness. These tools are particularly important in controller design, where ensuring stability and achieving desired performance are key objectives. However, when using advanced control techniques such as RL, LQR, and H_∞ synthesis, the presence of time delays introduces complexity. These methods, traditionally designed for systems without delays, are challenged by the infinite-dimensional nature of time-delay systems. In such cases, an approximation of the time-delay transfer function by rational polynomials is often required to make these methods viable. While this approximation can simplify the design process, it comes with trade-offs in accuracy and fidelity of system behaviour. Overall, this study highlights the importance of considering time delays in control system design and the need for careful approximation techniques when using advanced control methods. Future research should focus on refining these approximations and developing novel strategies for directly addressing time delays in more complex control frameworks. By doing so, we can improve the robustness and accuracy of controllers, especially in applications where delays play a significant role in system dynamics. This will contribute to more reliable and efficient control systems in various engineering domains.

Author Contributions

The percentages of the authors' contributions are presented below. The authors reviewed and approved the final version of the manuscript.

	C.Y.	A.A.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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Araştırma Makalesi (Research Article)
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KAHVERENGİ KOKARCA, *Halyomorpha halys* Stal (Hemiptera: Pentatomidae)'NIN İÇ FINDIKTAKİ ZARARININ TOPLAM FENOLİK, TOPLAM FLAVONOİD VE ANTİOKSİDAN AKTİVİTE ÜZERİNE ETKİSİ

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Özet: Bu çalışma, kahverengi kokarca, *Halyomorpha halys* (Hemiptera: Pentatomidae)'nın Palaz fındık (*Corylus avellana* L.) çeşidinde beslenmesi sonucu ortaya çıkan lekeli iç fındıklardaki biyoaktif bileşiklerin değişimini belirlemek amacıyla yürütülmüştür. Bu amaçla sağlıklı iç (Sİ) (kontrol), lekeli iç fındığın tamamı (LİT), lekeli iç fındığın sağlıklı kısmı (LİS) ve lekeli iç fındığın nekrotik (LİN) kısımlarındaki toplam fenolik, toplam flavonoid ve antioksidan aktivite belirlenmiştir. Sİ meyvelerine kıyasla zarar gören meyvelerde toplam fenolik, toplam flavonoid ve antioksidan aktivite artmıştır. En yüksek toplam fenolik LİN meyvelerinde (1781.3 mg 100 g^{-1}) belirlenirken, en düşük Sİ ve LİS meyvelerinde (sırasıyla 130.1 ve 275.4 mg 100 g^{-1}) tespit edilmiştir. Sİ (64.5 mg 100 g^{-1}) meyvelerine kıyasla en yüksek toplam flavonoid LİN meyvelerinde (679.0 mg 100 g^{-1}) belirlenmiştir. DPPH ve FRAP testlerine göre en yüksek antioksidan aktivite LİN meyvelerinde (sırasıyla 7.20 ve 49.10 mmol kg^{-1}) tespit edilmiştir. En düşük antioksidan aktivite ise Sİ meyvelerinde (sırasıyla 1.48 ve 18.55 mmol kg^{-1}) belirlenmiştir. Sonuç olarak, zarar gören fındık meyvelerindeki fenolikler, flavonoidler ve antioksidanlardaki artışın böcek kaynaklı biyotik strese karşı bitkinin doğal savunma mekanizmasından kaynaklandığı söylenebilir.

Anahtar kelimeler: Biyoaktif bileşikler, Böcek zararı, İstilacı, Kahverengi kokarca, Lekeli iç

Effect on Total Phenolic, Total Flavonoid, and Antioxidant Activity in Hazelnut Kernels Damaged By Brown Marmorated Stink Bug, *Halyomorpha Halys* Stal (Hemiptera: Pentatomidae)

Abstract: This study was carried out to determine the changes in bioactive compounds in necrotic kernels of Palaz hazelnut (*Corylus avellana* L.) cultivar damaged by brown marmorated stink bug (BMSB), *Halyomorpha halys* (Hemiptera: Pentatomidae). For this purpose, total phenolics, total flavonoids and antioxidant activity were determined in healthy kernel (HK) (control), whole of damaged kernel (WDK), healthy part of damaged kernel (HPDK) and necrotic part of damaged kernel (NPDK). The total phenolics, total flavonoids and antioxidant activity of the hazelnut kernel injured by BMSB increased as compared with the HK. The highest total phenolics was determined in NPDK (1781.3 mg 100 g^{-1}), while the lowest in HPDK and HK (130.1 and 275.4 mg 100 g^{-1}, respectively). The highest total flavonoids were determined in NPDK (679.0 mg 100 g^{-1}) compared to the HK (64.5 mg 100 g^{-1}). According to DPPH and FRAP assays, the highest antioxidant activity was determined in NPDK (7.20 and 49.10 mmol kg^{-1}, respectively), and the lowest in HK (1.48 and 18.55 mmol kg^{-1}, respectively). As a conclusion, the increase in phenolics, flavonoids, and antioxidants in the injured kernel can be due to the plant's natural defense mechanism against biotic stress because of the insect.

Keywords: Bioactive compounds, Brown marmorated stink bug, Insect damage, Invasive, Necrotic kernel

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1. Giriş

Pis kokulu böcekler (Hemiptera: Pentatomidae) dünya çapında 4700'den fazla türe sahip ve tarımsal açıdan önemli istilacı ve polifag zararlının bulunduğu bir gruptur (Panizzi ve ark., 2000; Grazia ve ark., 2015; Panizzi ve Lucini, 2017). Son yirmi yıl içinde dünya genelinde ve Türkiye'de hızla yayılan istilacı ve polifag bir zararlı olan kahverengi kokarca *Halyomorpha halys* (Hemiptera: Pentatomidae) bu gruptaki en önemli zararlıların başında gelmektedir ve 300'den fazla konukçusu ile pek çok kültür bitkisi için ciddi bir tehdit oluşturmaktadır (Rice ve ark., 2014; Hamilton ve ark., 2018; Ak ve ark., 2019). Amerika, Avrupa, Afrika, Kafkasya ve Türkiye'de yayılış gösteren zararlı (EPPO, 2024), ülkemizde halihazırda yayılışı için ekolojik uygunluk gösteren potansiyel alanlardan Karadeniz Bölgesi sahil şeridi boyunca önemli bir popülasyon oluşturarak yayılışına devam etmektedir (Kistner, 2017; Özdemir ve Tuncer, 2021; Ak ve ark., 2023). Fındığın ana üretim alanlarının bulunduğu bu bölge ülkemiz dünya fındık üretiminin %62'sini gerçekleştirmekte ve bu üretim ile dünya ihracatının %75'ini karşılamaktadır (FAO, 2022). Dolayısıyla, yetiştiricilik açısından hâkim kültür bitkisinin fındık olduğu bu bölgede zararlı ciddi bir ekonomik tehdit oluşturmaktadır (Özdemir ve Tuncer, 2021). Dahası, son 10 yıl içerisinde ABD (Hedstrom ve ark., 2014), İtalya (Bosco ve ark., 2018), Gürcistan (Murvanidze ve ark., 2018) ve son olarak Türkiye (Özdemir ve Tuncer, 2021) fındık bahçelerinde yüksek bir popülasyon oluşturan böcek, fındık üretimi için küresel bir tehdit haline gelmiştir. Kahverengi kokarca tüm hayat döngüsünü fındıkta tamamlayabilmekte ve zararlının erginleri ve nimfleri farklı fenolojik dönemlerde fındık meyvelerini sokup emerek farklı tiplerde zarara sebep olmaktadır. Fındığın kabuk genişleme döneminde zararlının beslenmesi sonucu boş fındık, iç gelişim sırasında meydana gelen beslenme sonucu şekilsiz iç ve iç olgunlaşma/olgunluk aşamasındaki beslenme sonucu ise lekeli/nekrotik iç zararı ortaya çıkmaktadır (Hedstrom ve ark., 2014). Türkiye'de fındık bahçelerinde en dominant tür olan fındık yeşil kokarcası, *Palomena prasina* L. (Hemiptera: Pentatomidae) başta olmak üzere pis kokulu böceklerden kaynaklanan ortalama %7.44 lekeli iç zararına sebep olmaktadır (Ak ve ark., 2018). Ek olarak, kahverengi kokarcanın diğer pis kokulu böceklere göre fındıkta daha yüksek üreme yeteneği ve beslenme aktivitesi nedeniyle daha yüksek bir oranda zarara sebep olduğu bilinmektedir (Bosco ve ark., 2018; Moraglio ve ark., 2018). Yukarıda da bahsedildiği üzere bu zararlar içerisinde özellikle lekeli iç zararı fındık kalitesini olumsuz etkilemekte ve hasat sonunda ek ayırma işlemi gerektirerek hem üreticilere ve hem de sanayicilere ek maliyetler oluşturmaktadır (Tuncer ve ark., 2005).

Pis kokulu böcekler, sokucu-emici ağız parçalarını kullanarak tükürük kılıflarını veya tükrük salgılarının konukçunun dokularına enjekte etmesiyle hücreleri parçalayarak konukçularından beslenmektedir (Lucini ve Panizzi, 2018a, b). Dolayısıyla bu familyada zarar kapasitesi en yüksek böceklerden birisi olan kahverengi kokarcaya ait zarar semptomları, tükrük salgılarının bitki dokularında oluşturduğu doku yaraları, renk değişimleri ve hatta meyve bağlamama şeklinde zararlar ile karakterize edilmektedir (Peiffer ve Felton, 2014). Biyotik stres altındaki kültür bitkileri böceklere karşı zararlı, kaçırıcı ve/veya beslenmeyi önleyici etkilere sahip terpenoidler, fenoller, antosiyaninler, kinonlar ve alkaloidler gibi çok çeşitli ikincil metabolitler üretir (War ve ark., 2012; Yactayo-Chang ve ark., 2020). Bitkilerin savunma kimyasalları normal bitki dokusu gelişimi sırasında bitkilerde bulunan önceden oluşturulmuş fenolikler ve herhangi bir zararlı böceğin verdiği zarara yanıt olarak sentezlenmeye başlanan fenolikler olmak üzere iki gruba ayrılabilir. Bu bileşiklerin sentezi hasarlı dokuda oluşabileceği gibi bitkinin diğer organlarına da transfer edilebilir (Lattanzio ve ark., 2012; Yactayo-Chang ve ark., 2020). Bitkilerde fenoliklerin sentezlenmesini başlatan jasmonat yolu, kahverengi kokarcanın beslenmesi sırasında salgılanan tükürüğün josmonatla tetiklenen genleri açığa çıkardığı ve bu yolu aktif hale getirerek fenolik içerikte artışa neden olduğu bildirilmiştir (Peiffer ve Felton, 2014). Fındık yeşil kokarcasının beslenmesi sonucu ortaya çıkan lekeli iç fındıkta (Turan, 2021; Özdemir ve ark., 2023a) ve kahverengi kokarcanın beslenmesi ile zarar gören maviyemişte (Zhou ve ark., 2016), çilekte (Weber ve ark., 2021) ve zeytinde (Ivancic ve ark., 2022) daha yüksek fenolik içerik rapor edilmiştir. Böcek zararı gibi biyotik stres faktörleri ile bitkilerdeki antioksidan aktivite arasında önemli bir ilişkinin varlığı (Reyes ve ark., 2007) ve fındıkta yeşil kokarca ve *Curculio nucum* L. (Coleoptera: Curculionidae) gibi çeşitli böceklerin zararının antioksidan enzim aktivitesini yükselttiği doğrulanmıştır (Özdemir ve ark., 2023a; Li ve ark., 2023). Türkiye'de yaygın olarak yetiştirilen Palaz fındık çeşidinin sadece kahverengi kokarca zararı sonucu ortaya çıkan kalite kaybının bireysel fenolikler ve yağ asitleri üzerine ayrıntılı analizleri yapılmış (Özdemir ve ark., 2023b) olup, haricinde herhangi bir çalışmaya rastlanmamıştır. Bu çalışmada kahverengi kokarcanın beslenmesi sonucu meydana gelen lekeli ve sağlıklı iç fındıklardaki toplam fenolik, toplam flavonid ve antioksidan aktivitenin belirlenmesi amaçlanmıştır.

2. Materyal ve Yöntem

2.1. Bitki materyali, lekeli içlerin elde edilmesi ve yetiştirme koşulları

Çalışmada Türkiye'de yaygın olarak yetiştirilen Palaz (*Corylus avellana* L.) fındık çeşidi kullanılmıştır.

Kahverengi kokarcanın sebep olduğu lekeli iç zararı bulunan fındıkları elde etmek amacıyla 12 yaşlı bir fındık bahçesinde yetiştirilen 'Palaz' çeşidinden 10 ocak seçildi ve her bir ocaktan en az 10 çotanak bulunan 2 dal seçilerek, 1 Mayıs 2022 tarihi itibariyle 50×100 cm tül kafesler kullanılarak toplamda 20 adet dal kafeslenmiştir. Her bir ocağa asılan iki kafesten birisi kontrol yani böcek

salınmayan (sağlıklı iç/böceklerden zarar görmeyen iç fındık için 10 kafes) ve böcekli kafesler (lekeli iç fındıkların elde edilmesi için 10 kafes) olarak değerlendirilmiştir. 25 Haziran 2022'de lekeli iç fındıkları elde etmek amacıyla böcekli kafeslere 4 adet ergin kahverengi kokarca salınmıştır. Rize ili Ardeşen ilçesinde kafesler için seçilen meyve bahçesinden (41°13'47.82 K enlemi, 41°5'47.96 D boylamı ve 144 m) toplanarak kafeslere salınan ergin böcekler hasada kadar kafeslerde tutulmuştur (Özdemir ve ark., 2023b). Hasat sırasında (3 Ağustos) kafeslerdeki fındıklar elle toplanmış ve böcekli veya kontrol olarak etiketlenerek laboratuvara taşınmıştır.

2.2. İç Fındıkların Analize Hazırlanması

Laboratuvara taşınan fındıklar havalandırmalı laboratuvar koşullarında 25 ± 1 °C sıcaklıkta kuruması için tezgâh üzerine yerleştirilerek, 10 gün boyunca %60–70 nemde bekletilmiş ve elle zuruflarından ayrılmıştır. Numuneler kurutulduktan sonra (yaklaşık %6 nem) +4 °C'de analize kadar bekletilmiştir. İç fındıklar kontrol/sağlıklı iç (Sİ), lekeli iç fındığın tamamı (LİT), lekeli iç fındığın sağlıklı kısmı (LİS), lekeli iç fındığın nekrotik kısmı (LİN) olmak üzere 4 gruba ayrılmıştır. Biyoaktif bileşikleri belirlemek için her gruptan yaklaşık 50 g iç fındık elde edilmiştir. Fındık tanelerinin hedef kısımları neşterle kazınarak, bütün içler/hedef kısımlar analiz için steril tüplere yerleştirilmiştir. Hazırlanan numunelerde biyoaktif bileşikler olarak toplam fenolik, toplam flavonoid ve antioksidan aktivite belirlenmiştir.

2.3. Toplam Fenolik

Fındık örneklerinin toplam fenolik içeriği Folin-Ciocalteu kimyasalı kullanılarak belirlenmiştir. Hazırlanan stok çözeltiden 600 µL alınarak üzerine 4 mL saf su, 100 µL Folin-Ciocalteu ve 300 µL sodyum karbonat ilave edilmiştir. Örneklerin absorbans değerleri spektrofotometrede (Shimadzu, Japonya) 760 nm dalga boyunda okunmuş ve mg 100 g^{-1} olarak ifade edilmiştir (Yılmaz ve ark., 2019).

2.4. Toplam Flavonoid

Toplam flavonoid içeriği Chang ve ark. (2002)'nın bildirdiği metot modifiye edilerek belirlenmiştir. Hazırlanan stok çözeltiden 1000 µL alınarak üzerine 3.3 mL metanol ilave edilmiştir. Daha sonra hazırlanan çözeltinin üzerine 100'er µL sodyum asetat ve amonyum nitrat eklenmiştir. Numunelerin absorbans değerleri spektrofotometrede (Shimadzu, Japonya) 415 nm dalga boyunda okunmuş ve mg 100 g^{-1} olarak ifade edilmiştir.

2.5. Antioksidan Aktivite

Fındık örneklerinin antioksidan aktivitesi DPPH ve FRAP yöntemlerine göre belirlenmiştir.

DPPH yöntemine göre antioksidan aktivitesi Blois (1958)'in metoduna göre tespit edilmiştir. Hazırlanan stok çözeltiden 100 µL alınarak üzerine 2.9 mL etil alkol ve son hacim 4 mL olacak şekilde 0.26 mM DPPH çözeltisi ilave edilmiştir. Örneklerin absorbans değerleri spektrofotometrede (Shimadzu, Japonya) 517 nm dalga boyunda okunmuş ve mmol kg^{-1} olarak ifade edilmiştir.

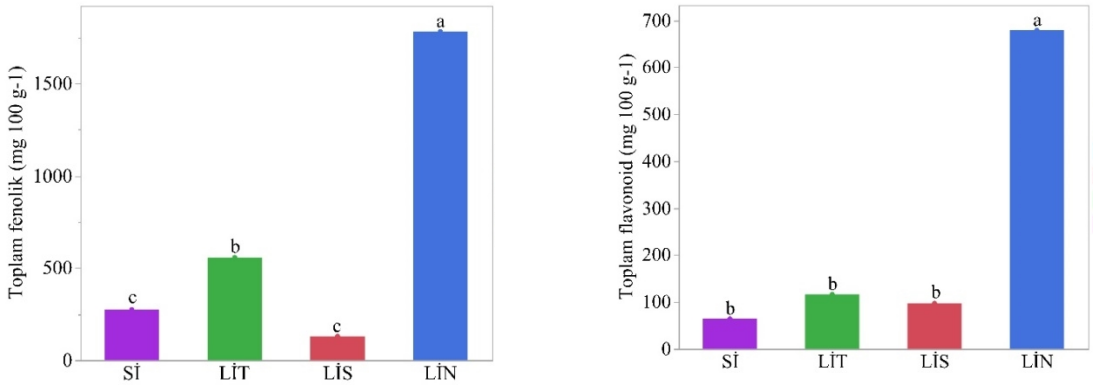
FRAP yöntemine göre antioksidan aktivitesi Benzie ve Strain (1996)'in rapor ettiği yönteme göre belirlenmiştir. Hazırlanan stok çözeltiden 40 µL alınarak üzerine 1.21 mL fosfat tamponu ve 1.25 mL potasyum ferrik siyanit ilave edilerek, 50°C'de 30 dk inkübasyona tabi tutulmuştur. Daha sonra hazırlanan çözeltinin üzerine 1.25 mL TCA ve 0.25 mL demir klorür eklenmiştir. Numunelerin absorbans değerleri spektrofotometrede (Shimadzu, Japonya) 700 nm dalga boyunda okunmuş ve mmol kg^{-1} olarak ifade edilmiştir.

2.6. İstatistik Analiz

Veriler JMP 14.0 (deneme sürümü) istatistik paket programı kullanılarak analiz edilmiş ve ortalamalar arasındaki farklılıklar %5 önem seviyesinde Tukey çoklu karşılaştırma yöntemine göre belirlenmiştir.

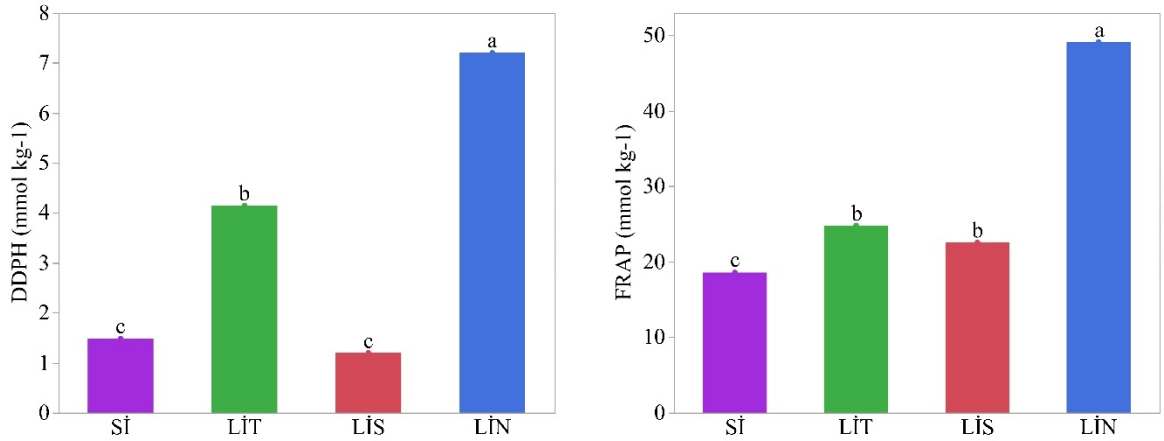
3. Bulgular

Toplam fenolik ve toplam flavonoid içerikleri üzerine kahverengi kokarcanın zararı önemli bulunmuştur ($P<0.05$). Sİ meyvelerine kıyasla kahverengi kokarca zararı olan meyvelerde fenolik ve flavonoid içerikleri artmıştır. En yüksek toplam fenolik LİN meyvelerinde (1781,3 mg 100 g^{-1}) belirlenirken, en düşük LİS ve Sİ (sırasıyla 130,1 ve 275,4 mg 100 g^{-1}) meyvelerinde tespit edilmiştir. En yüksek flavonoid içeriği LİN meyvelerinde (679,0 mg 100 g^{-1}) belirlenmiştir. En düşük toplam flavonoid içeriği ise Sİ meyvelerinde tespit edilirken, LİS ve LİT meyveleri istatistiki olarak aynı grupta yer almıştır (Şekil 1).



Şekil 1. Palaz fındık çeşidinde sağlıklı ve böcek zararı olan meyvelerin toplam fenolik ve toplam falvonoid içerikleri. Sİ= sağlıklı iç; LİT= lekeli iç fındığın tamamı; LİS= lekeli iç fındığın sağlıklı kısmı; LİN= lekeli iç fındığın nekrotik kısmı.

Antioksidan aktivite üzerine kahverengi kokarcanın zararı önemli bulunmuştur (P<0.05). Sİ meyvelerine kıyasla kahverengi kokarca zararı olan meyvelerde antioksidan aktivite önemli miktarda artmıştır. DPPH ve FRAP testlerine göre, en yüksek antioksidan aktivite LİN meyvelerinde (sırasıyla 7,20 ve 49,10 mmol kg^{-1}) belirlenmiştir. En düşük ise DPPH testine göre Sİ ve LİS meyvelerinde (sırasıyla 1,48 ve 1,20 mmol kg^{-1}), FRAP testine göre ise Sİ meyvelerinde (18,55 mmol kg^{-1}) tespit edilmiştir (Şekil 2).



Şekil 2. Palaz fındık çeşidinde sağlıklı ve böcek zararı olan meyvelerin antioksidan aktivitesi. Sİ= sağlıklı iç; LİT= lekeli iç fındığın tamamı; LİS= lekeli iç fındığın sağlıklı kısmı; LİN= lekeli iç fındığın nekrotik kısmı.

4. Tartışma

Fındık, insan sağlığını teşvik eden fenolikler ve antioksidanların önemli bir kaynağıdır. Fındıkta bulunan bu bileşikler üzerine biyotik (böcek veya patojen saldırıları) (Memoli ve ark., 2017) ve abiyotik (düşük ve yüksek sıcaklık, kuraklık, ultraviyole ışıkları) (Tonkaz ve ark., 2019; Khavari ve ark., 2021; Karakaya, 2023) stres faktörlerinin yanında, genetik yapı, ekolojik koşullar, kültürel ve teknik uygulamalar (sulama, gübreleme, budama) (Balta ve ark., 2006; Karakaya ve ark., 2023) da etki etmektedir.

Tüm bitkilerde biyotik ve abiyotik stres faktörlerine karşı savunma mekanizması olarak artan sekonder metabolitler (Yactayo-Chang ve ark., 2020) bitki zararlılarını olumsuz etkilemek, uzaklaştırmak veya kaçırmak için görev yapabilir. Nitekim, bitkiler strese karşı fenolik ve flavonoid sentezini artırarak böcekler üzerine etki etmekte ve bu sayede böceklerin meyveyle beslenmesini engellemeye çalışmaktadır (War ve ark., 2012; Adjei-Fremah ve ark., 2018; Weber ve ark., 2021).

Pis kokulu böcekler meyvelerde beslenme sırasında bitki dokularını tahrip ederek, proteinleri tirozin, fenilalanin ve triptofan gibi fenolik bileşiklere parçalayan proteinazların salınımına yol açmakta ve fenolik bileşiklerin artmasına sebep olmaktadır (Buchanan ve ark., 2015). Mevcut çalışmada da kahverengi kokarca ile enfekte olmuş fındıklarda (LİT, LİS ve LİN) zarara karşı gösterilen reaksiyon sonucu sekonder metabolitlerden fenolik bileşiklerin sentezi artmıştır. Bu durum bitkilerde strese karşı gösterilen yaygın bir tepkidir (Kaur ve ark., 2017). Mevcut çalışmanın sonuçlarıyla uyumlu olarak, fındık yeşil kokarcasının zarar yaptığı meyvelerde sağlıklı meyvelere (kontrol) göre daha yüksek toplam fenolik içeriği bildirilmiştir (Turan, 2021). Benzer şekilde, maviyemiş (Zhou ve ark., 2016), çilek (Weber ve ark., 2021) ve zeytin (Ivancic ve ark., 2022) gibi meyve türlerinde kahverengi kokarca zararı olan meyvelerde sağlıklı meyvelere (kontrol) göre daha yüksek toplam fenolik içeriği belirlenmiştir.

Flavonoidler bitkilerde savunma molekülleri olarak bilinirler (Soriano ve ark., 2004). Bitkide lezzeti etkileyen ve toksin görevi görebilen flavonoidler, emici böcekleri kaçırarak bitkileri zarara karşı koruduğu bildirilmektedir (Mierziak ve ark., 2014). Mısırda (*Zea mays*) yüksek miktarda bulunan flavonların *Ostrinia nubilalis* (Lepidoptera: Crambidae)'e karşı direnci artırdığı rapor edilmiştir (Yactayo-Chang ve ark., 2020). Yine, biberde kahverengi kokarca zararı olan meyvelerde yüksek flavonoid ve flavon içeriği belirlenmiştir (Zamljen ve ark., 2021). Benzer şekilde mevcut çalışmada da kahverengi kokarca zararı olan meyvelerde (LİT, LİS ve LİN) sağlıklı meyvelere (kontrol) göre daha yüksek flavonoid içeriği tespit edilmiştir.

Bitkilerde zarara neden olan biyotik stres faktörlerine karşı gösterilen tepkiyle antioksidan aktivite arasında güçlü bir ilişki vardır (Reyes ve ark., 2007). Mevcut çalışmada kahverengi kokarca zararı olan meyvelerde (LİT, LİS ve LİN), sağlıklı meyvelere (kontrol) göre daha yüksek antioksidan aktivite belirlenmiştir. Benzer şekilde zeytinde kahverengi kokarca zararı olan meyvelerde, sağlıklı meyvelere (kontrol) göre daha yüksek antioksidan aktivite bildirilmiştir (Ivancic ve ark., 2022). Bunun yanında, Palaz fındık çeşidinde fındık yeşil kokarcası zararı olan meyvelerde, sağlıklı meyvelere (kontrol) göre daha yüksek antioksidan enzim aktivitesi belirlenmiştir (Özdemir ve ark., 2023a). Fındık kurdu zararı olan 3 farklı fındık genotipinde de benzer sonuçlar kaydedilmiştir (Li ve ark., 2023). Böcek zararının olduğu meyvelerde yüksek antioksidan birikimi, zarar gören dokularda reaktif oksijen türlerinin proteinler, yağlar ve nükleik asitlere yönelik oksidatif zararı geciktirmesi ve önlemesiyle açıklanmaktadır (Arshiya, 2013).

5. Sonuç

Fındık meyvesinin toplam fenolik, toplam flavonoid ve antioksidan aktivitesi üzerine kahverengi kokarca zararının önemli bir etkisinin olduğu belirlenmiştir. Kahverengi kokarca zararı olan meyvelerde sekonder metabolitler önemli derecede artış göstermiştir. Sİ (sağlıklı iç/kontrol) meyvelerine kıyasla LİN (lekeli iç fındığın nekrotik kısmı) ve LİT (lekeli iç fındığın tamamı) meyvelerinde sırasıyla 6.5-2 kat toplam fenolik, 10.5-1.8 kat toplam flavonoid, 2.8-4.9 (DPPH testinde) ve 1.3-2.7 (FRAP testinde) kat antioksidan aktivitesi belirlenmiştir. Bu sonuçlar sekonder metabolitlerin bitki-böcek etkileşiminde önemli bir rol oynadığını göstermektedir.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	O.K.	İ.O.Ö.	U.A.	B.Ö.	M.U.	C.T.
K	30	30	10	10	10	10
T	30	30	10	10	10	10
Y	30	30	5	15	10	10
VTI	30	20	25	10	5	10
VAY	30	30	25	5	5	5
KT	30	30	10	10	5	15
YZ	35	35	10	5	5	10
KI	30	30	10	10	10	10
GR	25	30	30	5	5	5
PY	30	30	10	10	10	10

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

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DOĞAL GAZ BORU HATTI İNŞAATI MALİYETLERİNİN ÇOKLU DOĞRUSAL REGRESYON VE K-EN YAKIN KOMŞULUK YÖNTEMLERİ İLE TAHMİNİ

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Özet: Bu çalışmada, Türkiye sınırları içerisinde yapılacak olan doğal gaz boru hattı (DGBH) maliyetlerinin ön tahmini için makine öğrenmesi algoritmaları kullanılarak modeller geliştirilmiştir. Bunun için, 1997-2022 yılları arasında Türkiye'de tamamlanmış DGBH projelerinden elde edilen veriler kullanılmıştır. Projelerin boru çapı, hat uzunluğu, hat vanası sayısı, take-off vana sayısı ve pig istasyonu sayısı gibi değişkenleri, maliyet tahmininde bağımsız değişkenler olarak belirlenmiştir. Veri setinin nicel anlamda yetersiz ve veri kalitesinin ortalama bir seviyede olmasından dolayı, klasik makine öğrenmesi tahmin süreçleri yürütülememiştir. Bu nedenle, mevcut veri seti eğitim ve test bölümlerine ayrılmadan, bütün veri kullanılarak çalışılmış ve Çoklu Doğrusal Regresyon (ÇDR) ile K-En Yakın Komşu (KNN) algoritmalarına konumlandırıldığında modelin uygun bir şekilde performans gösterip göstermediği incelenmiştir. Bu çalışma, ileride veri kalitesinin ve sayısının artması durumunda, klasik makine öğrenmesi tahmin süreçlerinin yürütülüp yürütülemeyeceği konusunda ön fikir vermesi amacıyla gerçekleştirilmiştir. Her iki farklı yöntem denemesinde de benzer ve ortalama düzeyde belirleme katsayıları (R^2) elde edilmiştir. Sonuç olarak, bu çalışmada, DGBH projelerinde ön maliyet tahminlerinin hassasiyetini iyileştirmek için ÇDR ve KNN yöntemlerinin etkinliği karşılaştırılmış ve sektöre önemli bir katkı sağlayacağı değerlendirilmiştir. Gelecekte yapılacak çalışmaların daha geniş veri setleri ve farklı model teknikleri kullanarak maliyet tahminlerinin doğruluğunu artırabileceği ve sektör paydaşlarına yol gösterici olabileceği öngörülmektedir.

Anahtar kelimeler: Doğal gaz boru hatları, Makine öğrenmesi, Maliyet tahmini

Estimation of Natural Gas Pipeline Construction Costs Using Multiple Linear Regression and K-Nearest Neighbor Methods

Abstract: In this study, models were developed using machine learning algorithms for the preliminary estimation of natural gas pipeline (NGP) costs within the borders of Türkiye. For this purpose, data obtained from NGP projects completed in Türkiye between 1997 and 2022 were used. Variables such as pipe diameter, line length, number of line valves, number of take-off valves and number of pigging stations of the projects were determined as independent variables in the cost estimation. Since the data set was quantitatively insufficient and the data quality was at an average level, classical machine learning estimation processes could not be carried out. For this reason, the existing data set was studied using the entire data without dividing it into training and test sections, and it was examined whether the model performed appropriately when positioned in Multiple Linear Regression (MLR) and K-Nearest Neighbor (KNN) algorithms. This study was carried out to provide a preliminary idea about whether classical machine learning estimation processes can be carried out in the future if the data quality and number increase. Similar and average coefficients of determination (R^2) were obtained in both different method trials. As a result, in this study, the effectiveness of the MLR and KNN methods was compared to improve the accuracy of preliminary cost estimates in NGP projects and it was evaluated that it will make a significant contribution to the sector. It is anticipated that future studies can increase the accuracy of cost estimates by using larger data sets and different model techniques and can guide the sector stakeholders.

Keywords: Natural gas pipelines, Machine-learning, Cost estimate

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1. Giriş

Kabul edilebilir bir doğruluk seviyesinde yapılmış maliyet tahminleri proje başarısını doğrudan etkilemektedir (Adeli ve Wu, 1998; Kim ve ark., 2004; Arage ve Dharwadkar, 2017; Ibrahim ve Elshwadfy, 2021; Sueri ve Erdal, 2022). İnşaat sektörü projelerinde de ön maliyet tahmininin doğruluğu, proje maliyeti, işin tamamlanma süresi ve ürün/işçilik kalitelerinin belirlenmesinde kritik bir rol oynamaktadır. İnşaat sektörü, nicelik ve nitelik yönünden diğer sektörlere göre daha fazla risk faktörü ve belirsizlik parametresi barındırmaktadır (Birgönül ve Dikmen, 1996). Bu nedenle doğru ve güvenilir maliyet tahminleri yapmanın önemi daha da önem kazanmaktadır.

Doğal gaz boru hattı (DGBH) projeleri, büyük ölçekli yatırımlardır ve belirsizlik, hat uzunluğu ile doğru orantılı bir şekilde artmaktadır. Bu projelerde maliyet tahminlerinin doğruluğu, projelerin finansal sürdürülebilirliği ve operasyonel verimliliği açısından da hayati bir öneme sahiptir (Ugur ve ark., 2019). Hat uzunluğu, boru çapı, kullanılan malzemeler ve işçilik maliyetleri gibi değişkenler, proje maliyetini doğrudan etkileyen faktörler arasındadır (Parker, 2004; Rui ve ark., 2011a; Thaduri, 2012; Govan ve Reinschmidt, 2013; Erdal, 2021; Kaiser, 2021; Çakmak ve Erdal, 2022). Bu faktörlerin doğru bir şekilde tahmin edilmesi, projenin bütçe aşımına uğramadan tamamlanmasını ve kaynakların etkin bir şekilde kullanımını sağlamak için elzemdir.

Maliyet tahminlerinin doğruluğu, sadece proje yöneticileri için değil, aynı zamanda yatırımcılar, müteahhitler ve tedarikçiler için de kritik bir öneme sahiptir (Çakmak ve Erdal, 2022). Doğru maliyet tahminleri, yatırımcıların nakit akış eğrilerini daha hassas yönetmelerini sağlarken, uygulayıcı paydaşların da iş planlarını daha doğru bir şekilde yapmalarına olanak tanır.

Bu çalışmanın amacı, Türkiye'de gerçekleştirilen DGBH projelerinin maliyet tahminlerine odaklanmaktadır. Veri seti, 1997-2022 yılları arasında tamamlanmış projeleri içermektedir. Ancak, elde edilen verilerin sınırlı olması ve bazı projelere ilişkin eksik bilgiler, çalışmanın genel geçerliliğini kısıtlayabilir. Gelecekte yapılacak çalışmalar için daha geniş ve kapsamlı veri setlerinin kullanılması, maliyet tahminlerinin doğruluğunu artıracaktır. Kısıtlı bilgilerle maliyet tahmini yapabilmek için Çoklu Doğrusal Regresyon (ÇDR) ve K-En Yakın Komşu (KNN) modelleri oluşturulmuş ve sonuçları karşılaştırılmıştır.

2. Literatür Araştırması

İnşaat sektörü özelinde maliyet tahminini konu edinen ve regresyon ile hafıza tabanlı yöntemlerin kullanıldığı çalışma sayısı oldukça fazladır. Ancak özel olarak DGBH projelerine odaklanılan çalışma sayısı, diğer üst yapı ve alt yapı projelerine oranla literatürde kısıtlı bir alanı kaplamaktadır. Bu çalışmaların çoğunluğu Kuzey Amerika kıtasında yer alan projelerin verileri ile ortaya konan tahmin çalışmalarıdır. Yerel literatürde, DGBH projeleri ile ilgili bu projelerin jeopolitik önemi ve enerji dünyasındaki yerini tartışan çalışmalar bulunmakla birlikte maliyet anlamında irdelendiği herhangi bir çalışmaya rastlanılmamıştır. Bu çalışma, Türkiye'de gerçekleştirilen projelerin maliyet tahminlerine odaklanarak, literatürdeki bu boşluğu doldurmayı amaçlamaktadır. Bu bölümde kronolojik sıra göz önüne alınarak DGBH inşaatlarının maliyet tahminine odaklanılan çalışmalar sunulmuştur.

Zhao (2000) çalışmasında, DGBH inşaat maliyetlerinde kara üzerinde yapılanlar için %80, kara üzerinde olmayanlar için ise %84 kadarlık payı malzeme ve işçilik maliyetinin kapladığını belirtmiştir. Parker (2004) çalışmasında, doğal gaz, akaryakıt ve petrol boru hatlarının maliyetlerinden yola çıkarak hidrojen iletim hatlarında ne tür maliyet farklılıkları olabileceğini araştırmıştır. Parker, yaptığı araştırma ile birlikte doğal gaz boru hattı inşaat maliyetlerinin %26 malzeme maliyeti, %45 işçilik, %22 irtifak hakkı ve %7 çeşitli (araştırma, inceleme, sigortalar, izinler vb.) giderlerden oluştuğu sonucuna varmıştır. Yılmaz (2005) çalışmasında, petrol ve DGBH ile ilgili genel bir değerlendirme yapmıştır. İnşası devam eden ve inşaatı planlanan boru hatlarının detaylarının verildiği çalışmada araştırmacı, boru hatlarının Türkiye ekonomisine katkıda bulunacağını dile getirmiştir. Rui ve ark. (2011) çalışmalarında, 1992-2008 yılları arasında tamamlanmış 412 adet boru hattı projesinin maliyetlerini malzeme, işçilik, geçiş hakkı ve genel/çeşitli giderler üzerinden değerlendirmişlerdir. Çalışmada, işin tekrar tekrar yapılarak öğrenilmesinin işçilik maliyetlerini zamanla aşağıya doğru çektiğini belirtmişlerdir. Araştırmacılar yaptıkları bir diğer çalışmada ise aynı boru hatlarının bölgesel düzeyde maliyet farklılıklarını ortaya koymayı amaçlamışlardır. Çalışma kapsamında Amerika Birleşik Devletleri (ABD); Batı, Merkez, Güney Batı, Güney Doğu, Orta Batı ve Kuzey Doğu olarak farklı bölgelere bölünmüş ve en uygun maliyetlere Merkez bölgede ulaşıldığı belirlenmiştir (Rui ve ark., 2011a). Thaduri (2012) çalışmasında, 2000-2008 yılları arasında ABD ve Kanada sınırları içerisinde tamamlanmış 180 adet doğal gaz boru hattına ve 136 adet basınç istasyonuna ait verileri toplamış ve tanımlayıcı istatistiki veriler sunmuştur. Yapılan değerlendirmeler sonucunda araştırmacı, doğal gaz boru hattı maliyetlerinde en yüksek paya sahip maliyet kalemlerinin %40 ile işçilik ve %31 ile malzeme maliyeti olduğunu belirtmiştir. Rui ve ark. (2012), çalışmalarında boru hattı basınç istasyonu inşaatlarındaki maliyet hatalarını istatistiksel olarak sunmuşlardır. Ulvestad ve Overland (2012) doğal gaz ve CO_2 fiyatlarındaki değişimlerin LNG ve boru hattı taşımacılığının maliyet verimliliği üzerindeki etkilerini araştırdıkları bir çalışma gerçekleştirmişlerdir. Kaiser (2021) çalışmasında, ABD'deki doğal gaz boru hattı inşaatı ve devre dışı bırakma maliyetlerini detaylandırmış ve bu maliyetlerin bileşenleri ile teknik yeterliliklerin etkilerini incelemiştir. Ayrıca çalışmada, 2014-2019 yılları arasında gerçekleştirilen 99 adet projeye ait verilerle yapılan regresyon analizinde, boru hatlarının maliyetine hat uzunluğu ve boru çapı gibi faktörlerin önemli etkilerinin olduğu belirtilmiştir. Erdal (2021) çalışmasında, boru hattı projelerinin maliyet tahmini için 50 projelik bir veri seti kullanarak 6 farklı makine öğrenmesi algoritmasının başarı düzeyini incelemiştir. 10 katlı çapraz doğrulama tekniği uygulanan çalışmada, tüm yöntemler 0,79 ve üzerinde R^2 değeri elde etmiş ve Model Trees Regression yöntemi en başarılı yöntem olarak belirlenmiştir.

3. Materyal ve Yöntem

DGBH projeleri için bir erken maliyet tahmin modeli geliştirmek amacıyla Türkiye sınırları içerisinde yapılmış

olan 107 adet projenin bilgilerine ulaşılmıştır. İnternet siteleri, ihale duyuru ve bilgilendirme kaynakları, yüklenici firmaların kamuya açık sunduğu bilgiler, geçmiş meclis tutanakları ve Kamu İhale Kurumu sayfaları incelenerek, projelerin maliyet tahmininde kullanılabilecek parametreler elde edilmiştir. Detaylı incelemeler sonucunda 1997-2022 yılları arasında yapımı tamamlanmış DGBH projelerinin boru çapı, boru hattı uzunluğu, hat vanası sayısı, take-off vana sayısı ve pig istasyonu sayısı bilgileri, maliyet tahmininde kullanılabilecek bağımsız değişkenler olarak belirlenmiştir. Bu parametrelerin maliyet tahmini konusunda fikir verebileceği değerlendirilmiştir. Bu çalışma kapsamında metin içerisinde ve grafiklerde kullanılan değişkenlerin bilgi ve kısaltmaları Tablo 1'de, elde edilen verilerin tanımlayıcı istatistikleri ise Tablo 2'de verilmiştir.

Tablo 1. Değişkenlerin araştırma içerisinde gösterimi

Değişken	Model içerisinde kullanım	Kısaltma
Çap	diameter	D
Hat uzunluğu	length	L
Hat vanası	line_valve	LV
Take-off vanası	take_off_valve	TOV
Pig istasyonu	pigging_station	PS
Km başına birim maliyet	cost_km	-
Düzeltilmiş maliyet	adj_cost	C

Tablo 2. Veri setinin tanımlayıcı istatistikleri

Değişkenler	Adet	Ortalama	Standart Sapma	En Küçük	25. Yüzdelik	Medyan	75. Yüzdelik	En Büyük
diameter (inç)	107	19,68	13,37	6,00	10,00	14,00	36,00	48,00
length (km)	107	80,20	77,36	1,57	32,32	59,00	102,65	501,00
line_valve	107	2,40	2,73	0,00	1,00	2,00	3,00	17,00
take_off_valve	107	1,93	3,44	0,00	1,00	1,00	2,00	34,00
pigging_station	107	1,55	0,97	0,00	1,00	1,00	2,00	6,00
cost_km (bin $)	107	304,96	366,40	29,51	75,75	157,62	374,33	1.627,34
adj_cost (milyon $)	107	34,72	79,25	0,91	3,15	6,20	27,67	563,35

Tablo 2'de yer alan adj_cost parametresi, projelerin tamamlandığı tarihlerde ortaya çıkan ve Amerikan Doları cinsinden belirtilen maliyet değerlerinin, ABD'de kullanılan Consumer Price Index (CPI) değerlerine göre Mayıs 2024 tarihine dönüştürülmüş hâlini ifade etmektedir. Örnek bir hesaplama aşağıda sunulmuştur.

Mart 2004 tarihinde tamamlanmış bir projenin maliyeti yaklaşık 14.000.000,00 $ civarındadır. İlgili tarihte ABD tüketici fiyat endeksi (CPI) değeri ise 187,1 şeklindedir. Mayıs 2024 CPI değeri ise 313,225'tir. Bu durumda projenin düzeltilmiş maliyeti aşağıda şekilde ortaya çıkar. (eşitlik 1);

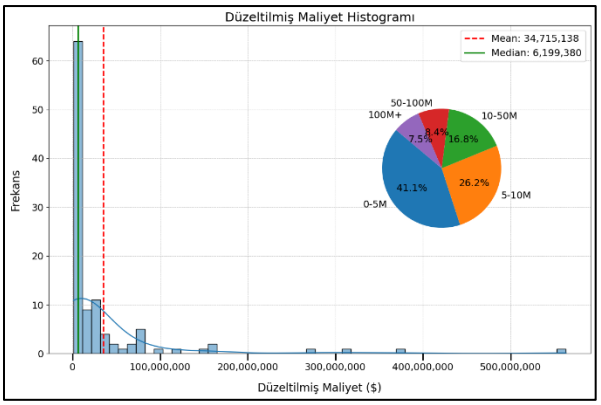
$$\text{Düzeltilmiş maliyet} = \frac{\text{Proje Tamamlanan Dönem Maliyeti}}{\text{Proje Tamamlanan Dönem CPI}} \text{x} \quad (1)$$

Dönüştürülecek ayın CPI değeri

$$\text{Düzeltilmiş maliyet} = \frac{14.000.000,00}{187,1} \text{x } 313,225$$

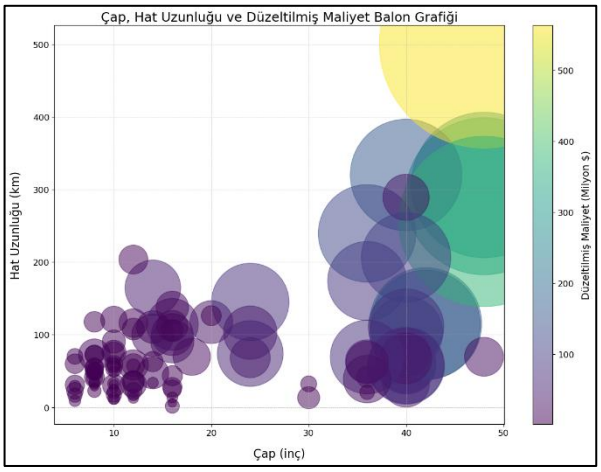
$$= 23.437.467,60\ \$$$

Tablo 2'de yer alan, cost_km parametresi ise hesaplanan adj_cost parametresinin DGBH uzunluğuna bölünmesi ile elde edilen bir değişkendir. Bu parametre ile DGBH projelerinde km başına oluşan birim maliyetler belirlenmiştir. cost_km değişkeni ayrıca bu çalışmanın model bölümünde bahsedilen uç değer atma işlemi için de kullanılacak bir parametredir. Bu değişken ile birlikte adj_cost ve length değişkenleri birlikte değerlendirilmiş ve uç değer tespit adımında kullanılmıştır. Veri setinde küçük, orta, büyük ve mega projeler yer aldığından, büyük ve mega proje sayısının diğer proje sayısından daha az olmasından kaynaklı sağa çarpık bir veri dağılımı söz konusudur. Veri setinin düzeltilmiş maliyet histogram grafiği Şekil 1'de verilmiştir.



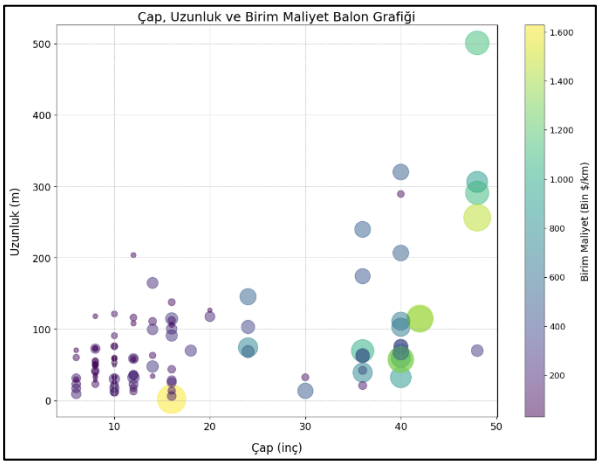
Şekil 1. Maliyet histogram grafiği.

Veri setinin daha iyi anlaşılabilmesi için boru çapı ve hat uzunluğuna bağlı olarak maliyet değişkeninin yayılımını gösteren grafik Şekil 2'de gösterilmiştir.

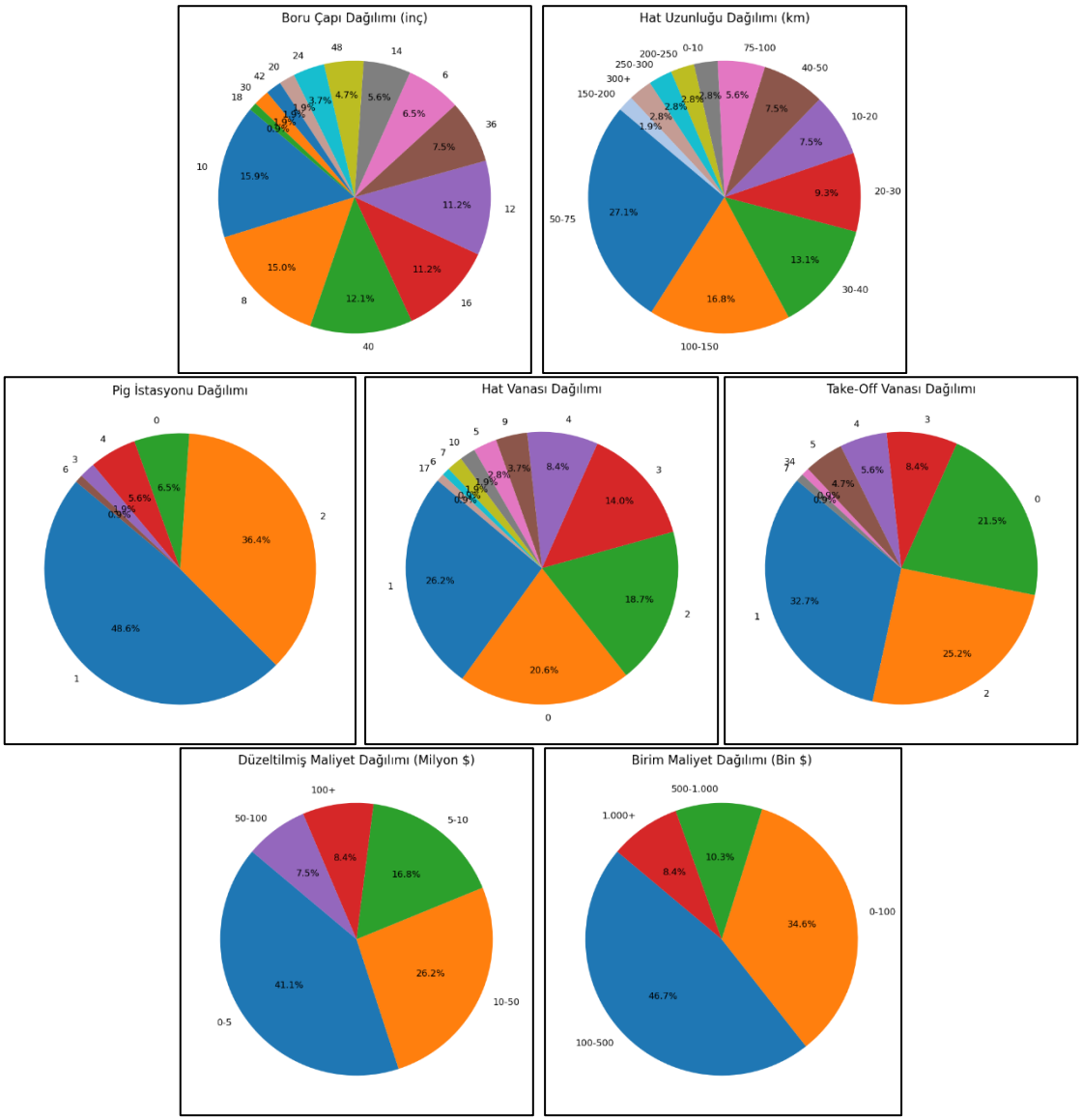


Şekil 2. Çap ve hat uzunluğu değişkenlerine göre toplam proje maliyeti.

Şekil 2 detaylı bir şekilde incelendiğinde, genel eğilim boru çapı ve hat uzunluğunun artmasıyla proje maliyetinin de arttığı yönündedir. Bu durumda, bu değişkenlerle birlikte bağımlı değişken olan düzeltilmiş maliyet verisinin doğru orantılı olduğu yorumunu yapmak mümkündür. Ancak bazen düşük çap ve hat uzunluklarında dâhi yüksek maliyetlerin ortaya çıkabildiği de grafikten görülebilir. Her iki parametre ile birlikte, km başına ortaya çıkan birim maliyet verisinde de orantılı bir artış gerçekleşmektedir. Ancak buna rağmen düşük hat uzunluğuna ve boru çapına sahip projelerde de yüksek km başına birim maliyet değerleri gözlemlenebilmektedir. Hatta en yüksek km başına birim maliyet verisi, çap ve hat uzunluğu değişkeninin oldukça düşük olduğu bir bölgede yer almaktadır. Çap ve hat uzunluğu parametrelerine karşın km başına düşen birim maliyeti gösteren grafik Şekil 3'te sunulmuştur. Ayrıca veri setinde yer alan tüm bağımlı-bağımsız değişkenlerin pasta grafikleri Şekil 4'te gösterilmiştir.



Şekil 3. Çap ve hat uzunluğu değişkenlerine göre km başına maliyet.



Şekil 4. DGBH proje maliyet tahmin parametrelerinin pasta grafikleri.

3.1. Modeller

Mevcut veri seti içerisinde yer alan, veriyi sağa çarpık kılan ve uç değerler olarak adlandırılan değişkenler analiz sonuçlarını olumsuz yönde etkilemektedir. Bu durum ortaya konulan modellerin başarı metriklerini de aşağıya doğru çekmektedir. Bundan dolayı, veri setinin bir miktar daha normal dağılıma yaklaşmasını sağlayacak olan uç değerli veri atma işlemi gerçekleştirilmiştir. IQR (Interquartile Range) ile uç değer tespit işlemi yaygın olarak kullanılmaktadır (Hubert ve ark., 2007). Bu araştırma özelinde veri setindeki uç değerleri tespit etmek için de IQR yöntemi kullanılmıştır. IQR değerinin hesaplanması için aşağıdaki matematiksel işlemin (Eşitlik 2) yapılması gerekmektedir.

$$IQR = Q3 - Q1 \quad (2)$$

Burada;

- Q1 = Toplam veri sayısının en düşük %25'lik kısmını ayıran değerdir.
- Q3 = Toplam veri sayısının en düşük %75'lik kısmını (en yüksek %25) ayıran değerdir.

IQR hesaplandıktan sonra uç değer tespiti için alt sınır ve üst sınırların hesaplanması gerekmektedir. Sınır değerler aşağıdaki şekilde (Eşitlik 3 ve Eşitlik 4) hesaplanmıştır.

$$\text{Alt sınır} = Q1 - 1.5 \times IQR \quad (3)$$

$$\text{Üst sınır} = Q3 + 1.5 \times IQR \quad (4)$$

Gözlem değerlerinde alt sınırın altında kalan ve/veya üst sınırın üstünde olan tüm gözlemler uç değer olarak nitelendirilmiş ve veri setinden çıkarılmıştır. Jupyter notebook ortamında Python aracılığıyla yazılan kod Şekil 5'te verilmiştir. Sonuç çıktısı ise Tablo 3'de sunulmuştur.

```python
# IQR yöntemi ile outlier tespiti ve temizleme fonksiyonu
def remove_outliers_iqr(df, columns):
    Q1 = df[columns].quantile(0.25)
    Q3 = df[columns].quantile(0.75)
    IQR = Q3 - Q1
    is_not_outlier = ~((df[columns] < (Q1 - 1.5 * IQR)) |(df[columns] > (Q3 + 1.5 * IQR))).any(axis=1)
    return df[is_not_outlier]
```

Şekil 5. Uç değer tespit fonksiyonu kodu

Tablo 3. Modele esas veri seti tanımlayıcı istatistikleri

Değişkenler	Adet	Ortalama	Standart Sapma	En Küçük	25. Yüzdelik	Medyan	75. Yüzdelik	En Büyük
diameter (inç)	88	15,48	10,20	6,00	8,00	12,00	16,00	48,00
length (km)	88	59,01	37,53	6,00	31,64	54,53	74,29	203,47
line_valve	88	1,69	1,49	0,00	1,00	1,00	3,00	7,00
take_off_valve	88	1,99	3,72	0,00	1,00	1,00	2,00	34,00
pigging_station	88	1,52	0,96	0,00	1,00	1,00	2,00	6,00
cost_km (bin $)	88	173,40	164,98	29,51	64,93	114,54	206,09	776,82
adj_cost (milyon $)	88	10,33	11,93	0,91	2,54	5,19	12,91	55,60

Tablo 3'de yer alan tanımlayıcı istatistikler, uç değerlerden temizlenmiş veri setinin istatistikleridir. Bu veri seti ile modeller oluşturulmuş ve model başarı parametreleri R^2 değerleri üzerinden gözlemlenmiştir. Karşılaştırma yapmak için kök ortalama kare hatası (RMSE) değeri hesaplanmıştır. R^2, modelde bağımsız değişkenlerin bağımlı değişkeni ne kadar iyi açıkladığını gösteren istatistiksel bir ölçüttür. 0 ile 1 arasında bir değer alır ve değerin 1'e yakın olması, modelin veriyi daha iyi açıkladığı anlamına gelir. RMSE ise modelin tahmin ettiği değerler ile gerçek değerler arasındaki ortalama farkı ölçen bir hata metriğidir. Değerin düşük olması, modelin tahminlerinin gerçeğe daha yakın olduğunu gösterir. R^2 ve RMSE değerlerinin hesaplanma yöntemi Eşitlik 5 ve Eşitlik 6'da gösterilmiştir.

$$R^2 = 1 - \frac{SS_{residual}}{SS_{total}} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (5)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (6)$$

Burada;

- y_i, i-inci gözlemin gerçek değerini,
- $\bar{y}$, bağımlı değişkenin ortalama değerini,
- $\hat{y}_i$, modelin tahmin ettiği i-inci gözlemin değerini,
- n, toplam gözlem sayısını temsil eder.

3.1.1. Çoklu doğrusal regresyon (ÇDR)

ÇDR, bir bağımlı değişkenin birden fazla bağımsız değişken ile olan ilişkisinin modellenmesine odaklanılan basit bir yöntemdir. ÇDR, bağımsız değişkenlerin bağımlı değişken üzerindeki etkilerini anlamak, tahmin etmek ve analiz etmek için kullanılır. ÇDR modeli, aşağıdaki genel denkleme (Eşitlik 7) dayanır:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \quad (7)$$

Burada;

- β_0 modelin sabit terimidir.
- β_1, β_2, ..., β_n her bir bağımsız değişkenin katsayılarıdır. Bu katsayılar, bağımsız değişkenlerin bağımlı değişken üzerindeki etkisini gösterir.
- ε ise hata terimidir ve modelin açıklayamadığı rastgele hataları içerir.

ÇDR analizi statsmodels kütüphanesi kullanılarak yapılmıştır. Statsmodels kütüphanesi bu tarz regresyon problemleri için kullanıcıya sağladığı ve model hakkında bilgi veren yararlı ara yüzüyle istatistiksel modellemeler amacıyla yaygın olarak kullanılan kütüphanelerden birisidir (Seabold ve Perktold, 2010). Model süreci için adımlar ve model çıktıları aşağıda verilmiştir.

a) Model süreci aşamaları için gerekli kütüphanelerin import edilmesi: Jupyter notebook ortamında kütüphanelerin yüklenebilmesi için genellikle import ifadesi kullanılır. Şekil 6'daki kod parçacığı bu işlemin yapılması için yazılması gereken metni göstermektedir.

```python
import statsmodels.api as sm
```

Şekil 6. Statsmodels kütüphanesi import kodu.

b) Verinin okunması: Bu adımda Pandas kütüphanesi yardımı ile excel dosyasındaki veriler okunmuştur. Excel dokümanında istenen sütun değerlerinin okutulabildiği kod parçacığı Şekil 7'de verilmiştir.

```python
ngpc = pd.read_excel(
"C:\\Users\\cosku\\ngpc_veriler.xlsx",
 usecols=["diameter",
          "length",
          "line_valve",
          "take_off_valve",
          "pigging_station",
          "adj_cost",
          "cost_km"]        )
```

Şekil 7. Excel verilerinin okutulması.

c) Bağımlı-bağımsız değişkenlerin belirlenmesi ve sabit eklenmesi: Bu adımda excel dokümanından çekilen değişkenlerin hangilerinin bağımsız, hangilerinin bağımlı değişken olduğunun modele

tanıtılma işlemi yapılmaktadır. Şekil 8'deki kod parçası "ngpc" isimli veri setinin değişkenlerini gruplamaktadır. Statsmodels içerisindeki "add_constant" fonksiyonu yardımıyla da bağımsız değişken X'e sabit eklenmektedir. Böylece Eşitlik 7'de yer alan β_0 sabiti, sonuç denklemi elde edildiğinde denklem içerisinde yer alabilmektedir.

```
X = ngpc.drop(["adj_cost", "cost_km"], axis=1)
y = ngpc["adj_cost"]

X=sm.add_constant(X)
```

Şekil 8. Değişken gruplaması ve sabit eklenmesi.

d) Modelin fit edilmesi ve sonuçların gösterimi: Makine öğrenmesi algoritmalarında verilerin modele uyup uymadığının kontrolü ve modelin eğitilmesi amacıyla "fit()" fonksiyonu kullanılmaktadır. Bu adımda değişkenler statsmodels kütüphanesinin ÇDR algoritmasına gönderilmekte ve bağımsız değişkenlerin bağımlı değişken üzerindeki açıklayabilme oranları tespit edilmektedir. Bu işlemin gerçekleşmesini sağlayan kod parçacığı Şekil 9'da gösterilmiştir.

```
tüm_veri_çdr = sm.OLS(y, X).fit()
tüm_veri_çdr.summary()
```

Şekil 9. Değişkenlerin modele fit edilmesi.

Bu adımda yer alan summary fonksiyonu ile Tablo 4 ve Tablo 5'de yer alan sonuçlar elde edilmiştir.

Tablo 4. Regresyon modeli başarı metrikleri

Dep. Variable:	adj_cost	R-squared:	0,581
Model:	OLS	Adj. R-squared:	0,556
Method:	Least Squares	F-statistic:	22,75
No. Observations:	88	Prob (F-statistic):	3,01e-14
Df Residuals:	82	Log-Likelihood:	-1520,0
Df Model:	5	AIC:	3052
Covariance Type:	nonrobust	BIC:	3067

Tablo 5. Değişken katsayıları ve anlamlılık düzeyleri

Parametreler	coef	std err	t	P>|t|	[0.025	0.975]
const	-4,43e+06	2,69e+06	-1,647	0,103	-9,79e+06	9,22e+05
diameter	6,35+05	9,21e+04	6,893	0,000	4,52e+05	8,18e+05
length	1,10e+05	4,04e+04	2,717	0,008	2,94e+04	1,9e+05
line_valve	5,32e+06	1,04e+06	0,511	0,611	-1,54e+06	2,6e+06
take_off_valve	2,37e+05	2,39e+05	0,992	0,324	-2,39e+05	7,13e+05
pigging_station	-1,91e+06	9,75e+05	-1,963	*0,053*	-3,85e+06	2,56e+04

Tablo 4 incelendiğinde model, bağımlı değişkendeki değişkenliğin %58 oranında açıklanabildiğini göstermektedir. Tablo 5, boru çapı ve hat uzunluğu parametrelerinin, proje maliyeti üzerinde en etkili değişkenler olduğunu ortaya koymaktadır. Diğer değişkenlerin ise 0,05'ten daha büyük p değerlerine sahip olmaları sebebi ile ÇDR ile model kurulurken bağımlı değişken üzerindeki varyans değerinin açıklanmasında yetersiz oldukları sonucu ortaya çıkmaktadır. Ancak pigging_station değişkeni sınır değere oldukça yakın olduğundan dolayı tekrarlanacak olan modelde kullanılmasına karar verilmiştir. Bu kapsamda ÇDR modellemesi için boru çapı, hat uzunluğu ve pig istasyonu parametreleri kullanılıp, diğer parametreler dışarıda tutularak tekrarlanmıştır. Ayrıca model içerisinde bir sabit olmasının anlamlı olmadığı 0,103 (P>0,05) değerine sahip olan p değerinden anlaşılmaktadır. Dolayısıyla bu durum modelin başarısını etkileyebileceğinden, düzenlenecek olan modelde veri setine sabit ekleme işlemi gerçekleştirilmemiştir. Böylece genelleme açısından daha doğru bir modelin ortaya çıkacağı değerlendirilmiştir. Şekil 10'da yalnızca model için anlamlı olan değişkenlerin tutulmasına, diğer değişkenlerin dışarıda kalmasına ve denklemde sabit bir katsayı olmadan regresyon kurma işlemi gerçekleştirmeye olanak tanıyacak kod parçacığına yer verilmiştir. Tablo 6 ve Tablo 7'de ise bu kod parçacığının sonuç çıktısı yer almaktadır.

```
X = ngpc_clean.drop(["adj_cost", "cost_km", "line_valve", "take_off_valve"], axis=1)
y = ngpc_clean["adj_cost"]

tüm_veri_çdr = sm.OLS(y, X).fit()
tüm_veri_çdr.summary()
```

Şekil 10. İstatistiksel olarak anlamlı (p<0,05) bağımsız değişkenlerle model fit etme işlemi

Tablo 6. Üç değişkenli regresyon modeli başarı metrikleri

Dep. Variable:	adj_cost	R-squared:	0,748
Model:	OLS	Adj. R-squared:	0,739
Method:	Least Squares	F-statistic:	53,65
No. Observations:	88	Prob (F-statistic):	8,54e-16
Df Residuals:	85	Log-Likelihood:	-1552,4
Df Model:	3	AIC:	3051
Covariance Type:	nonrobust	BIC:	3058

Tablo 7. Üç değişkenli regresyon modeli değişken katsayıları ve anlamlılık düzeyleri

Parametreler	coef	std err	t	P>|t|	[0.025	0.975]
diameter	5,39e+05	6,89e+04	7,825	0,000	4,02e+05	6,76e+05
length	1,171e+05	2,21e+04	5,306	0,000	7,32e+04	1,61e+05
pigging_station	-2,887e+06	7,38e+05	-3,912	0,000	-4,35e+06	-1,42e+06

Eşitlik 6 aracılığıyla hesaplanan RMSE değeri ise 7.679.373,12 $ düzeyinde hesaplanmıştır. Bu değer uç veriler atıldıktan sonra ortaya çıkan tanımlayıcı istatistiklere bakıldığında düzeltilmiş maliyet verisinin ortalamasına yakın bir değerdir ve görece yüksek olduğu değerlendirilebilir.

Son durumda DGBH projelerinin maliyet tahmininde kullanılabilecek model denklemi Eşitlik 8'de verilmiştir.

C($)=539.049,5×**D**+117.093,69×**L**–2.887.226,57×**PS** (8)

3.1.2. K-en yakın komşu (KNN)

KNN, gözetimli öğrenme algoritmaları arasında yer alan ve hem sınıflandırma hem de regresyon problemlerinde kullanılan basit ve etkili bir yöntemdir. Bu yöntem, yeni bir verinin sınıfını belirlemek veya değerini tahmin etmek için en yakın K komşusunun etiketlerine veya değerlerine bakar. Bu algoritma, belirli bir noktanın yakınındaki diğer noktalarla olan benzerliğine dayanarak çalışır (Bentley, 1975).

KNN algoritması şu temel adımları içerir:

I. **Veri Kümesinin Hazırlanması:** Algoritma, veriler üzerinde çalışır. Her bir veri noktası, özellik vektörlerine ve etiketlerine sahiptir.

II. **Mesafe Hesaplama:** Yeni bir veri noktası geldiğinde, bu noktanın tüm eğitim veri noktalarına olan mesafesi hesaplanır. Genellikle Öklidyen mesafesi kullanılır, ancak Manhattan veya Minkowski mesafesi gibi diğer mesafe metrikleri de kullanılabilir.

Öklidyen mesafesi, iki veri noktası arasındaki en kısa doğrusal mesafeyi hesaplar ve Eşitlik 9 ile ifade edilir:

$$d(p,q) = \sqrt{\sum_{i=1}^{n}(p_i - q_i)^2} \quad (9)$$

Manhattan mesafesi, koordinat eksenlerine paralel yolların toplam uzunluğunu hesaplar (Eşitlik 10).

$$d(p,q) = \sum_{i=1}^{n}|p_i - q_i| \quad (10)$$

Minkowski mesafesi, genelleştirilmiş bir mesafe hesaplama yöntemidir ve Eşitlik 11'de verilmiştir.

$$d(p,q) = \left(\sum_{i=1}^{n}|p_i - q_i|^p\right)^{1/p} \quad (11)$$

Burada:

- p ve q veri noktalarını,
- p_i ve q_i veri noktalarının i'inci özellik değerlerini temsil eder.

III. **K Komşusunun Seçimi:** Hesaplanan mesafelerden en küçük olan K tanesi seçilir. Bu komşular, yeni veri noktasının en yakın K komşusu olarak belirlenir.

IV. **Tahmin Yapma:** Regresyon problemlerinde, K komşusunun ortalama değeri alınarak tahmin yapılır.

KNN regresyon için kullanılan karar kuralı Eşitlik 12 ile hesaplanır:

$$\hat{y} = \frac{1}{K}\sum_{i=1}^{K} y_{N_k(x_i)} \quad (12)$$

Burada:

- $\hat{y}$ yeni veri noktasının tahmin edilen değerini,
- $y_{N_k(x_i)}$ K komşusunun gerçek değerlerini temsil eder.

Bu bölümde scikit-learn kütüphanesi kullanılarak KNN analizi yapılmıştır. Scikit-learn, makine öğrenmesi algoritmaları ve veri işleme adımları için geniş kapsamlı bir kütüphanedir (Buitinck ve ark., 2011). KNN modeli için adımlar ve çıktıları aşağıda açıklanmıştır.

KNN, yukarıda bahsedildiği şekliyle mesafelere dayalı bir tahmin modeli kurduğu ve mevcut veri setinde birbirinden farklı ölçeklerde değişkenler yer aldığı için değişkenlerin ölçeklendirilmesi gereklidir. Bu bölümde ÇDR düzeyinde basit olmayan, modelin en iyi parametrelerinin araştırıldığı (hiperparametre ayarlama) bir model oluşturulmuştur. Model için adımlar ve çıktıları aşağıda açıklanmıştır.

a) Model aşamaları için gerekli kütüphanelerin import edilmesi: KNN modeli için gerekli import işlemini gerçekleştiren kod Şekil 11'de gösterilmiştir.

```
from sklearn.neighbors import KNeighborsRegressor
```

Şekil 11. KNN kütüphanesi import kodu.

b) Verinin okunması: Veri seti değerlerinin okutulabildiği kod parçacığı Şekil 12'de verilmiştir.

```
ngpc = pd.read_excel(
"C:\\Users\\cosku\\ngpc_veriler.xlsx",
 usecols=["diameter",
          "length",
          "line_valve",
          "take_off_valve",
          "pigging_station",
          "adj_cost",
          "cost_km"]        )
```

Şekil 12. Excel verilerinin okutulması.

c) Uç değerler atılarak bağımlı-bağımsız değişkenlerin belirlenmesi; IQR yönteminin fonksiyonu ve değişken sınıflamasını sağlayan kod Şekil 13'te verilmiştir.

```
outlier_degiskenler = ["cost_km", "adj_cost", "length"]
ngpc_clean= remove_outliers_iqr(ngpc, outlier_degiskenler)

X=ngpc_clean.drop(["cost_km", "adj_cost"], axis=1)
y=ngpc_clean["adj_cost"]
```

Şekil 13. Uç değerlerin atılması ve değişken gruplaması.

d) Standardizasyon: Standartlaştırma, KNN algoritmasının performansını ve doğruluğunu artıran kritik bir adımdır. Bu süreç, farklı birimlerdeki değişkenlerin aynı ölçek üzerinde karşılaştırılabilir olmasını sağlar. Özellikle veri setindeki değişkenlerin farklı ölçeklerde olduğu durumlarda, standartlaştırma adımı KNN algoritmasının daha etkili çalışmasına katkıda bulunur. Scikit-learn bünyesinde yer alan StandardScaler'ın import edilmesi ve değişkenlerin standart sapmasının 1, ortalamalarının ise 0 olmasını sağlayacak kod parçacığı Şekil 14'te verilmiştir.

```
from sklearn.preprocessing import StandardScaler

scaler = StandardScaler()
X_scaled = scaler.fit_transform(X)
```

Şekil 14. Değişkenlerin standartlaştırılması.

e) Modelin oluşturulması ve fit edilmesi: Şekil 15'te KNN model nesnesinin hiperparametreleri görülmektedir.

```
# KNN modeli (Tune Öncesi)
knn = KNeighborsRegressor()
knn.fit(X_scaled, y)
knn
```

```
KNeighborsRegressor(algorithm='auto', leaf_size=30, metric='minkowski',
                    metric_params=None, n_jobs=None, n_neighbors=5, p=2,
                    weights='uniform')
```

Şekil 15. Değişkenlerin modele fit edilmesi ve varsayılan parametre değerleri.

Şekil 15'ten görüldüğü üzere KNN modeli varsayılan olarak belirli parametrelerle modeli oluşturmaktadır. Bunlardan en önemlileri ve sonraki adımlarda ayarlamaya çalışılacak olanlar ise n_neighbors ve leaf_size parametreleridir. n_neighbors parametresi yeni bir veri noktası oluşturulurken modelin en yakınındaki kaç gözleme uğrayacağını belirtir. leaf_size ise KNN içerisinde ağaç yapıları şeklinde saklanan veri kümelerinde en fazla ne kadar veri tutulması gerektiğini gösteren bir parametredir. Modelde görülen değerler bir başlangıç noktası olarak düşünülmelidir. Bu başlangıç noktasının en iyi değerler olabileceği ihtimâli de göz ardı edilmemelidir.

f) Tahmin ve sonuçlar: Varsayılan parametreler ile Şekil 16'da kod parçacığı gösterilen model çalıştırıldığında R^2=0,690 ve RMSE=6.625.707,23 $ değerleri elde edilmiştir. Bu öncül değerlendirmenin ardından modelin n_estimator ve leaf_size parametreleri değiştirilerek, en iyi belirleme katsayısına ulaşılmaya çalışılmıştır.

```
y_pred = knn.predict(X_scaled)

R2_score_train_BT = r2_score(y, y_pred)
RMSE_train_BT = np.sqrt(mse(y, y_pred))
```

Şekil 16. Model başarı parametreleri olan R^2 ve RMSE hesaplaması.

g) Hiperparametre ayarlama işlemi ve sonrasında tahmin ve sonuçlar: Hiperparametre ayarlama işlemi, yani KNN model nesnesinin en iyi hangi parametrelerle çalıştığının araştırılması sürecinde GridSearchCV yöntemi kullanılmıştır. GridSearchCV, bir modelin hiperparametrelerini sistematik olarak denemek ve en iyi performans gösteren kombinasyonu belirlemek için kullanılan bir çapraz doğrulama yöntemidir. Bu yöntem, modelin doğruluğunu artırmak ve aşırı uyum sorunlarını azaltmak amacıyla farklı parametre setlerini değerlendirir (Şekil 17).

```
knn_params = {'n_neighbors': [3, 4, 5, 6, 7, 8, 9, 10],
              'leaf_size': [20, 30, 40]    }

# KNN modeli için en iyi hiperparametreleri bulma
knn_grid = GridSearchCV(KNeighborsRegressor(),
                        knn_params,
                        cv=5,
                        scoring='r2')
knn_grid.fit(X_scaled, y)

# En iyi parametreler ile KNN modelini eğitme
best_knn = knn_grid.best_estimator_

# Modeli eğit
best_knn.fit(X_scaled, y)

# Tune sonrası tahmin yap
y_pred = best_knn.predict(X_scaled)

R2_score_train_AT = r2_score(y, y_pred)
RMSE_train_AT = np.sqrt(mse(y, y_pred))
```

Şekil 17. Hiperparametre ayarlama işlemi ve model başarı metriklerinin hesaplanması.

Hiperparametre ayarlama işlemi sonrası elde edilmiş parametreler ile model çalıştırıldığında R^2=0,660 ve RMSE=6.934.296,43 $ değerleri ortaya çıkmıştır. Bu değer ayarlanmış hiperparametreler ile elde edildiği için güvenilirliği daha fazladır.

4. Tartışma ve Sonuç

Bu çalışmada, Türkiye'de gerçekleştirilen DGBH proje maliyetlerinin, çeşitli proje parametreleri ile iki farklı model aracılığıyla tahmin başarısı belirlenmeye çalışılmıştır. Verilerde yer alan nicel kısıtlılık sebebiyle klasik model üretme ve tahmin yapma sürecinden farklı olarak mevcut veriler ÇDR ve KNN modellerine yerleştirilmiş ve maliyet üzerindeki açıklama kapasitesi düzeyi tespit edilmeye çalışılmıştır. Yöntemlerde bağımsız değişkenler olarak boru çapı, hat uzunluğu, hat vanası sayısı, take-off vana sayısı ve pig istasyonu sayısı parametreleri kullanılmıştır.

ÇDR modelinde, boru çapı ve hat uzunluğu parametreleri maliyet üzerinde en etkili değişkenler olarak belirlenmiş ve bu değişkenlerin bağımlı değişkendeki varyans değerinin %75'ini açıklayabildiği (R^2=0,748) belirlenmiştir. KNN modelinde varsayılan parametrelerle elde edilen belirleme katsayısı R^2 = 0,690 olup, ayarlanmış hiperparametreler ile bu değer 0,660 olarak bulunmuştur.

Sonuçlar, mevcut veri setinin kısıtlılığına rağmen her iki yöntemin de maliyet tahmininde makul ancak yeterli olmayan bir performans sergilediğini göstermektedir. Elde edilen R^2 değerleri yüksek olmasa da, veri kalitesinin ve sayısının artması durumunda tahmin doğruluğunun önemli ölçüde artabileceğini göstermektedir. Daha geniş ve kaliteli veri setleri elde edilerek maliyet tahmin modellerinin doğruluğu artırılabilir. Mevcut veri setinin kısıtlılığı nedeniyle sadece belirli parametreler kullanılmıştır. Veri setine daha fazla ve farklı parametrelerin (Örn; zemin cinsleri, işçilik ücretleri, kamulaştırma bedelleri vb.) eklenmesinin mümkün olduğu koşullarda, hem klasik makine öğrenmesi süreçlerinin işletilebileceği hem de model performans başarı metriklerinde gözle görülür iyileşmeler sağlanacağı düşünülmektedir. SMOGN (Synthetic Minority Over-sampling Technique for Regression) gibi sentetik veri artırma yöntemleri kullanılarak bu tarz tahmin çalışmalarının tekrarlanması ve bu sayede modellerin genelleme özelliğinin artırılması mümkün olabilecektir. Farklı makine öğrenmesi algoritmaları kullanılarak (Örn; ağaç yöntemleri, rastgele ormanlar, destek vektör makineleri vb.) maliyet tahminlerinin doğruluğu artırılabilir. Ayrıca veri ön işleme süreçlerinin iyileştirilmesi ve uç değerlerin daha etkin yönetilmesinin de model performansını artırabileceği değerlendirilmiştir. Bu çalışma, doğalgaz boru hattı projelerinde maliyet tahminleri konusunda önemli bir başlangıç noktası oluşturmaktadır ve gelecekte yapılacak araştırmalara ışık tutacaktır.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	C.Ç.	M.E.
K	70	30
T	70	30
Y	10	90
VTI	40	60
VAY	80	20
KT	90	10
YZ	80	20
KI	20	80
GR	80	20
PY	10	90

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

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GELENEKSEL ERZURUM EVLERİ VE 'LEED RESİDENTİAL: SİNGLE FAMİLY' DEĞERLENDİRME SİSTEMİ

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Özet: Geleneksel konut yapıları, geleneksel sistemler ile inşa edilen diğer yapı türleri gibi; malzeme, alan yönetimi, enerji kullanımı gibi birçok açıdan sürdürülebilir kabul edilen yapılardır. Günümüzde yeni konut yapıları için sürdürülebilirlik anlamında değerlendirme sistemleri bulunmakla birlikte; tarihi geleneksel konut yapıları için özelleştirilmiş ve yaygın olarak kabul görmüş bir değerlendirme sistemi bulunmamaktadır. Bu durum, sürdürülebilir anlayışla üretilen geleneksel yapıların sistematik bir sürdürülebilirlik değerlendirmesine katılamamasına sebep olmaktadır. Bir başka eksiklik de bu yapıların ilk halleri ile günümüze ulaşmış mevcut halleri arasındaki farklılıklara ve bu farklılıkların yapıların sürdürülebilirliklerine olan etkilerine ait değerlendirmelerin olmayışıdır. Yapılarda sürdürülebilirlik düzeylerini ölçen yeşil bina sertifikasyon sistemlerin içerisinde, tüm dünyada kabul gören ve yaygın olarak kullanılan ve öncü sayılabilir bir konumda olan LEED değerlendirme sistemleri yer almaktadır. İnsan ve doğayı göz önünde bulundurarak daha iyi konutlar inşa edebilmek adına Leed Residential Single Family değerlendirme sistemi yeni konut yapılarındaki sürdürülebilirlik düzeylerini belirlemede kullanılmaktadır. Yapılan bu çalışma ile Leed Residential: Single Family değerlendirme sisteminde yer alan kriterler üzerinden geleneksel konutlar için sürdürülebilirlik değerlendirmesi yapılabilecek kriterler tespit edilmiş; geleneksel Erzurum evleri özelinde geleneksel konut yapılarının ilk hallerine ait bir sürdürülebilirlik değerlendirmesi gerçekleştirilmiştir. Geleneksel konutlar için sürdürülebilir bir değerlendirmede; değerlendirmeye alınamayan kriterler ile hangi kriterler üzerinde durulması gerektiği tartışılmış, yapıların ilk halleri ve günümüze ulaşmış mevcut hallerindeki farklılıklar içerisinde yer alan ekler ile ilgili olarak değerlendirme kriterlerine yönelik önerilerde bulunulmuştur. Geleneksel Erzurum evlerinin sürdürülebilirliklerinin değerlendirildiği bu çalışma ile bu yapıların, "konum ve ulaşım" ile "enerji ve atmosfer" alanlarında oldukça başarılı oldukları; "malzeme ve kaynaklar" ile "iç ortam kalitesi" alanlarında ise çoğunlukla başarılı oldukları görülmüştür.

Anahtar kelimeler: Geleneksel konut, Tarihi yapılar, Erzurum evleri, Leed, Yeşil bina sertifikasyon sistemleri

Traditional Erzurum Houses and LEED Residential: Single Family Rating System

Abstract: Traditional residential structures, like other buildings constructed with traditional methods, are considered sustainable in various aspects, such as materials, space management, and energy use. Although there are assessment systems currently available for evaluating the sustainability of new residential buildings, no widely accepted and specialized evaluation system exists for historical traditional houses. This lack of a dedicated framework prevents systematically assessing the sustainability of these historically sustainable buildings. Another significant gap is the absence of evaluations addressing the differences between the original forms of these structures and their current states, as well as the impact of these changes on their sustainability. Among green building certification systems that assess sustainability, the LEED evaluation system is recognized globally as a leading and widely accepted framework. The LEED Residential: Single Family assessment system is used to determine the level of sustainability in new residential buildings, considering human and environmental factors to promote better housing construction. This study identifies potential criteria for assessing the sustainability of traditional houses based on the criteria in the LEED Residential: Single Family evaluation system. Focusing on traditional Erzurum houses, the study conducts a sustainability assessment of these structures in their original forms. In conducting a sustainability evaluation of traditional houses, the study discusses which criteria should be emphasized and which cannot be applied. Recommendations are also made regarding the criteria for assessing extensions and alterations that differentiate the original structures from their current forms. The findings from the sustainability assessment of traditional Erzurum houses reveal that these structures perform notably well in the "location and transportation" and "energy and atmosphere" categories, and are generally successful in the "materials and resources" and "indoor environmental quality" categories.

Keywords: Traditional housing, Historic buildings, Erzurum houses, Leed, Green building certification systems

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1. Giriş

Çevrenin ihtiyaçları çoğu zaman insanla çelişmektedir (Bartlett, 1994). Bunlardan biri olan yapı ve yapım endüstrisi ise, malzeme tüketiminin %40'ından ve toksik gazların üretiminin %40-50'sinden sorumlu olmaları nedenleriyle sürdürülebilirlik konusunda en önem verilmesi gereken sektörlerin başında gelmektedirler (Kofoworola ve Gheewala, 2008). Belirtilen çevresel etki içerisinde; eşyaların nasıl yapıldığının, binaların nasıl inşa edildiğinin ve peyzajların nasıl kullanıldığının bir sonucu olarak görülen ekolojik krizinin aslında sürdürülemez bir tasarım krizi olduğu söylenebilmektedir.

Heinberg ve Lerch'e (2010) göre sürdürülebilirlik kavramı, tüm uzun vadeli planlamaların temel taşı ve vazgeçilemez olmalıdır. McLennan (2004), sürdürülebilir tasarımı; "binaların çevreye karşı daha sorumlu ve insanlara karşı daha duyarlı olacak şekilde tasarlanması, inşa edilmesi ve işletilmesini yeniden tanımlamaya çalışan bireylerin ve kuruluşların büyüyen hareketinin felsefî temelidir" şeklinde açıklamıştır. Bu tasarım felsefesi; doğal çevre üzerindeki olumsuz etkileri en aza indirirken veya ortadan kaldırırken yapılı çevrenin kalitesini en üst düzeye çıkarmayı amaçlamaktadır (McLennan, 2004).

Belirtilen felsefeyi uygulamaya dökmek amacı ile İngiltere'de 1990 yılında ilk yeşil bina sertifikasyon sistemi olan BREEAM geliştirilmiştir (Uruk ve Külünkoğlu İslamoğlu, 2019). Amerika'da ise, 1993 yılında ABD Yeşil Bina Konseyi (USGBC)'nin kurulması sonrasında bu konsey tarafından 1997 yılında LEED yeşil bina sertifikasyon sistemi oluşturulmuştur (Aksoy ve ark., 2013). Bu iki sertifikasyon sisteminin ortaya konuluşunu izleyen yıllarda farklı ülkeler tarafından oluşturulan farklı yeşil bina sertifikasyon sistemleri ortaya çıkmıştır. 2012 yılında ise, geliştirilen sertifikasyon sistemlerini tek bir çatı altında toplarken aynı zamanda yeni sertifikasyon sistemlerinin oluşturulmasını da hızlandıran Dünya Yeşil Bina Konseyi (WGBC) kurulmuş; sayısı 70'in üzerinde olan ülkelerin yeşil bina konseylerinin her biri kendi ülkesi özelinde yeşil bina sertifikasyon sistemlerini oluşturmuşlardır (World Green Building Council, 2021; Varma ve Palaniappan, 2019).

Her ne kadar ülkelerin kendilerine ait yeşil bina sertifikasyon sistemleri bulunsa da dünya üzerinde halen yaygın olarak kullanılan sertifikasyon sistemlerinin en yaygın kullanılanı olarak LEED göze çarpmaktadır (Amiri ve ark., 2019). LEED sertifikasyon sistemine bakıldığında, yapı ölçeğine ve yapı türlerine bağlı olarak farklı sertifikasyon türlerini içerisinde barındırdığı gözlenmektedir (Kubba, 2009). Bu sistemlerinden bir tanesi de yeni konut yapılarının sürdürülebilirlik düzeylerini ölçmek için oluşturulmuş Leed Residential: Single Family isimli sertifikasyon sistemidir. LEED tarafından oluşturulan bu sürdürülebilirlik değerlendirme sistemi, ana başlık ve bu başlıklara ait kriterlerden oluşmakta ve diğer sertifikasyon sistemleriyle paralellik göstermektedir (Tablo 1).

Geleneksel mimari, usta çırak ilişkisi ile deneyim yoluyla kendiliğinden gelişim göstermiş, yöreye özgü malzemelerin ve yapım yöntemlerinin kullanıldığı, iklimsel verileri ve arazi yapısını dikkate alan tasarım ürünleridir (USGBC, 2024; Halifeoğlu ve ark., 2020). Çevresel ve kültürel etmenlerin yanında sosyal ve bireysel etmenler de bu mimarinin şekillenmesinde rol almaktadırlar (Batur ve Gür, 2005). Geleneksel mimari ve konutlar içerisindeki geleneksel Türk evi; temel düzeni ve öğelerinin yerleşimindeki özgünlüğü ile geniş bir tarihi ve coğrafyayı kapsayan geleneksel bir anlayışın ürünüdür. Bektaş'a (2013) göre; doğaya, çevre koşullarına ve yaşama uygunluk, gerçekçilik, akılcılık, içten dışa çözüm, iç-dış uyumu (evin iç mekanındaki yalınlığın dışa vurumu gibi), tutumsallık (tutumluluk), yapım yöntemlerinde kolaylık, ölçülerinin insana uygunluğu, çevresel gereçlerin kullanımı ve esneklik (büyüyebilme, küçülebilme, bölünebilme) ilkelerinden meydana getirilmiştir. Türk evi, yayıldığı birbirinden farklı topraklarda yöresel malzeme ve iklim koşullarına uyma zorunluluğunun yanında yerli geleneklerin benimsenmesinden çeşitli tipler meydana getirmiştir (Eldem, 1984). Özellikle İslamiyet sonrası Türklerin Anadolu'ya göçü ile birlikte Türk kültürü içerisinde yani konut tipolojileri meydana getirilmiştir (Şahin ve Dinçer, 2024). Kültürel süreklilik içerisinde Türklerin doğayla bütünleşmiş yaşam değerleri doğrultusunda üretilen Türk evi, üretildiği çevreye uyum göstererek evrimleşmiştir (Sözen, 2001).

Anadolu'da üretilen geleneksel Türk konut yapılarından biri de bölgesel dağılıma göre Doğu Anadolu'da inşa edilen ve kendine özgü özellikler taşıyan Erzurum evleridir. Sözen'e (2001) göre, ataerkil büyük aile tipinin geçerli olduğu geleneksel kültürün ürünü olan bu evler; iklim koşullarının olumsuzluklarına karşı kalın kesme taş duvar örgüsünde belli aralıklarla yatay ahşap hatıl kullanımıyla biçimlenmişlerdir. Erzurum evleri, planlarında 'tandır evi'nin bulunması bakımından bölgede yer alan diğer geleneksel konut tipolojilerinden farklılık göstermektedir (Sağlam ve Yurttaş, 2020). Bunun yanında, kendine özgü bir yapı örtüsü olan ve konutta yer alan tandır evinin üstünü örten 'kırlangıç kubbe'ye de bu evlerde görülmektedir. Bu anlamda Erzurum evlerinin diğer geleneksel konut tiplerinde olduğu gibi kendine has yöresel özellikler taşıdığı; bu anlamda, malzeme başta olmak üzere iklimsel yaklaşımının da sürdürülebilirlikle ilişkili olabileceğini söylemek mümkündür.

Tablo 1. Leed residential: single family v4.1 değerlendirme kriterleri (USGBC, 2024)

Leed v4.1	Residential: Single Family	Puan
Entegrasyon Süreci 2 puan	Entegrasyon Süreci	2
	Taşkın yatağından kaçınma	Zorunlu
	Mahalle gelişim konumu için LEED	10
Konum ve Ulaşım	Alan seçimi	6
10 puan	Kompakt gelişim	1
	Toplumsal kaynaklar	1
	Ulaşıma erişim	2
	İnşaat faaliyetlerinde kirliliğin önlenmesi	Zorunlu
Sürdürülebilir Alanlar	Isı adası azaltımı	1
5 puan	Yağmur suyu yönetimi	2
	Toksik olmayan/Zehirsiz haşere kontrolü	2
	Su Kullanımı	Zorunlu
	Su Ölçümü	Zorunlu
Su Verimliliği 15 puan	Toplam su kullanımı	15
	İç mekân su kullanımı	11
	Dış mekân su kullanımı	4
	Minimum enerji performansı	Zorunlu
	Enerji ölçümü	Zorunlu
	Ev sahibi, kiracı veya bina yöneticisinin eğitimi	Zorunlu
Enerji ve Atmosfer	Yıllık enerji kullanımı	36
40 puan	Verimli sıcak su dağıtım sistemi	2
	Isıtma, havalandırma ve iklimlendirme (HVAC) yetki belgesi	1
	Soğutucu yönetimi	1
	Sertifikalı tropikal ahşap	Zorunlu
	Dayanıklılık yönetimi	Zorunlu
Malzeme ve Kaynaklar	Dayanıklılık yönetimi doğrulaması	3
12 puan	Çevresel açıdan tercih edilebilir ürünler	5
	İnşaat atık yönetimi	2
	Malzeme verimli taşıyıcı sistem	2
	Havalandırma	Zorunlu
	Isıtma havalandırması	Zorunlu
	Garaj kirletici koruması	Zorunlu
	Radon dayanıklı yapı	Zorunlu
İç Ortam Kalitesi	Hava filtreleme	Zorunlu
16 puan	Bölmelendirme	Zorunlu
	Gelişmiş havalandırma	3
	Kirletici kontrolü	2
	Isıtma/Soğutma dağıtım sistemlerinin dengelenmesi	6
	Düşük emisyonlu ürünler	4
İnovasyon 6 puan	Ön değerlendirme	Zorunlu
	Yenilik	5
	LEED Onaylı evler	1
	Bölgesel öncelik: Özel kredi	1
Bölgesel Öncelik	Bölgesel öncelik: Özel kredi	1
4 puan	Bölgesel öncelik: Özel kredi	1
	Bölgesel öncelik: Özel kredi	1
Toplam	Alınabilir puan	110

Geleneksel konut mimarisini oluşturan ve etkileyen etmenler, Erzurum evleri dışında araştırıldığında; bu etmenlerin sürdürülebilirlikle olan ilişkileri açıkça görülmektedir (Gezer, 2013). Bu sebeple; geleneksel konut yapılarının çevreye uyumlu yapılar olarak sürdürülebilir tasarımlar oldukları görüşü hakimdir (Canan ve ark., 2020; Kıstır ve Kurtoğlu, 2018). Geleneksel konut yapıları ve sürdürülebilirlik ilişkisini araştırmak üzere farklı konu başlıkları ve ülkelerin geleneksel konutları üzerinde gerçekleştirilen çalışmalar bulunmaktadır (Abdelmonem, 2007; Adeli ve Abbasi, 2014; Soflaei ve ark., 2017; Abdul Majid ve ark., 2017; Sokienah, 2020; Samalavicius ve Traskinaite, 2021). Geleneksel konut yapıları ile ilgili Leed sertifikasyon sistemi üzerinden yapılan ve konuya katkı sağlayan çalışmalar da bulunmaktadır (Taygun, 2019; El Sorady ve Rizk, 2020; Taygun ve ark., 2021). Özellikle Leed v4.1 Residential: Single Family sertifikasyon sisteminin ele alınarak konunun geneli ile ilgili yapılan bir çalışmaya rastlanılmamıştır. Leed v4.1 Residential: Single Family sertifikasyon sistemi üzerinden Erzurum evleri özelinde sürdürülebilirlik değerlendirmesi gerçekleştiren bu çalışma ile literatürdeki bu eksikliğin giderilmesi ve geleneksel konut mimarisinde sürdürülebilirlik değerlendirmesi açısından öneri/ler sunulması hedeflenmektedir.

2. Materyal ve Yöntem

Çalışmanın örneklemini, Doğu Anadolu Bölgesi'nde yer alan geleneksel konut yapılarından Erzurum evleri oluşturmaktadır. 2024 yılı itibariyle, Erzurum ili merkez ilçesi olan Yakutiye içerisinde; Erzurum Kültür Varlıklarını Koruma Kurulu tarafından tescillenmiş (123) ve tescili kaldırılmış (15) toplam 138 adet sivil mimari örneği olan konut bulunmaktadır. Yapılan çalışma kapsamında, Erzurum Kalesi'nin güney cephesine yakın konumda bulunan altı geleneksel konut yapısı seçilmiştir (Şekil 1). Bu yapıların seçiminde, kale ve çevresinde uygulanan kültür yolu projesi kapsamında restorasyonları yapılarak günümüzde de aktif olarak kullanılan yapılar olması etkin rol oynamıştır.

Şekil 1. Örneklem yapılarının konumları ve alan yerleşimleri.

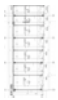
Çalışma kapsamında ele alınan altı geleneksel konut yapısına ait bilgiler, plan şekilleri ve görseller Tablo 2'de yer almaktadır. Tablo 3'e göre; Leed v4.1 sertifikasyon sistemi kapsamında yer alan entegrasyon süreci, inovasyon ve bölgesel öncelik ana başlıkları ile sürdürülebilir alanlar ana başlığı altında yer alan inşaat faaliyetlerinde kirliliğin önlenmesi kriteri yapının inşa süreci ile ilgili veri eksikliği nedeni ile tarihi yapılar için uygulanamamaktadır. Enerji ve atmosfer ana başlığı altında yer alan; minimum enerji performansı, enerji ölçümü ve yıllık enerji kullanımı kriterleri ile ilgili bir değerlendirme yapabilmek adına söz konusu ölçümler için yeterli veriye ulaşılamamıştır. Bu bakımdan, söz konusu kriterler de çalışmanın kapsamı dışarısında bırakılmışlardır.

Çalışmanın üçüncü aşamasında, geleneksel yapıların sürdürülebilirliklerinin Leed v4.1 üzerinden yeniden ele alınarak oluşturulan sürdürülebilirlik değerlendirme kriterleri doğrultusunda irdelenmesi hedeflenmektedir. Bu sebeple, yapının restorasyonu kapsamında sonradan yapıda gerçekleştirildiği tespit edilen elektrik, su, yapay aydınlatma ve iklimlendirme uygulamalarına ait kriterler ile geleneksel konutların yapıldığı tarihlerde uygulanamayacak kriterler de çalışmanın dışında tutulmuştur.

Çalışmanın ikinci ve üçüncü aşamasında sürdürülebilirlik kriterleri ile ilgili gerçekleştirilen değerlendirme sonucunda, çalışma kapsamında ele alınan sürdürülebilirlik değerlendirme kriterleri ve puanlama sistemi yeniden oluşturularak Tablo 4'te verilmiştir.

Çalışmanın son aşamasında, çalışmada ele alınan geleneksel konutlara uygulanacak olan sürdürülebilirlik değerlendirme kriterleri (Tablo 4) oluşturulduktan sonra alan çalışması ve veri toplama aşamasına geçilmiştir. Bu aşamada; geleneksel konutlar ile ilgili kurumlar aracılığı ile veriler toplanmış, konutlar üzerinde alanda gerekli incelemeler gerçekleştirilmiş ve kriterler özelinde bulgular elde edilmiştir.

Tablo 2. Örneklem yapılarına ait bilgiler, plan şekilleri ve görseller

Yapı Tescil No	Görseli	Zemin ve Kat Planı	I.(ve II.) Kat Plan(lar)ı
1 391			
2 213			
3 214			
4 212			
5 300			
6 313			

Tablo 3. Değerlendirme kriterlerinin çalışmada kullanılma ve çalışmadan dışlanma durumları

Leed v4.1	Residential: Single Family	Puan
Entegrasyon Süreci 2 puan	Entegrasyon Süreci	2
	Taşkın yatağından kaçınma	Zorunlu
	Mahalle gelişim konumu için LEED	10
Konum ve Ulaşım	Alan seçimi	6
10 puan	Kompakt gelişim	1
	Toplumsal kaynaklar	1
	Ulaşıma erişim	2
	İnşaat faaliyetlerinde kirliliğin önlenmesi	Zorunlu
Sürdürülebilir Alanlar	Isı adası azaltımı	1
5 puan	Yağmur suyu yönetimi	2
	Toksik olmayan/Zehirsiz haşere kontrolü	2
	Su Kullanımı	Zorunlu
	Su Ölçümü	Zorunlu
Su Verimliliği 15 puan	Toplam su kullanımı	15
	İç mekân su kullanımı	11
	Dış mekân su kullanımı	4
	Minimum enerji performansı	Zorunlu
	Enerji ölçümü	Zorunlu
	Ev sahibi, kiracı veya bina yöneticisinin eğitimi	Zorunlu
Enerji ve Atmosfer	Yıllık enerji kullanımı	36
40 puan	Verimli sıcak su dağıtım sistemi	2
	Isıtma, havalandırma ve iklimlendirme (HVAC) yetki belgesi	1
	Soğutucu yönetimi	1
	Sertifikalı tropikal ahşap	Zorunlu
	Dayanıklılık yönetimi	Zorunlu
Malzeme ve Kaynaklar	Dayanıklılık yönetimi doğrulaması	3
12 puan	Çevresel açıdan tercih edilebilir ürünler	5
	İnşaat atık yönetimi	2
	Malzeme verimli taşıyıcı sistem	2
	Havalandırma	Zorunlu
	Isıtma havalandırması	Zorunlu
	Garaj kirletici koruması	Zorunlu
	Radon dayanıklı yapı	Zorunlu
İç Ortam Kalitesi	Hava filtreleme	Zorunlu
16 puan	Bölmelendirme	Zorunlu
	Gelişmiş havalandırma	3
	Kirletici kontrolü	2
	Isıtma/Soğutma dağıtım sistemlerinin dengelenmesi	6
	Düşük emisyonlu ürünler	4
İnovasyon 6 puan	Ön değerlendirme	Zorunlu
	Yenilik	5
	LEED Onaylı evler	1
	Bölgesel öncelik: Özel kredi	1
Bölgesel Öncelik	Bölgesel öncelik: Özel kredi	1
4 puan	Bölgesel öncelik: Özel kredi	1
	Bölgesel öncelik: Özel kredi	1
Toplam	Alınabilir puan	110
	Çalışmadan dışlanan kriter	
	Çalışmada kullanılan kriter	

Tablo 4. Çalışma kapsamında geleneksel konutlara uygulanacak sürdürülebilirlik değerlendirme kriterleri

Ana Başlıklar	Kriterler	Puan
Konum ve Ulaşım 10 puan	Taşkın yatağından kaçınma	Zorunlu
	Alan seçimi	6
	Kompakt gelişim	1
	Toplumsal kaynaklar	1
	Ulaşıma erişim	2
Sürdürülebilir Alanlar 3 puan	Isı adası azaltımı	1
	Yağmur suyu yönetimi	2
Enerji ve Atmosfer 1 puan	Soğutucu yönetimi	1
Malzeme ve Kaynaklar 10 puan	Dayanıklılık yönetimi doğrulaması	3
	Çevresel açıdan tercih edilebilir ürünler	5
	Malzeme verimli taşıyıcı sistem	2
İç Ortam Kalitesi 4 puan	Havalandırma	Zorunlu
	Düşük emisyonlu ürünler	4
Toplam	Alınabilir puan	28

3. Bulgular ve Tartışma

Alanda yapılan incelemeler ışığında yapıların sürdürülebilirlik değerlendirmesi Tablo 5'te görülmektedir. Tabloya göre Konum ve ulaşım ana başlığı açısından bütün yapıların uygun tasarımlara sahip olduğu görülmüştür. Binalar taşkın yatağından kaçınacak şekilde konumlandırılmıştır. Alan seçimleri yapıldıkları tarihlerde güvenlik açısından kaleye yakın olmaları nedeni ile iyi bir tercihtir. Bunun yanı sıra kompakt bir şehir gelişimi görülmesini desteklemektedir. Dönemin toplumsal kaynaklarının kale ve çevresinde şekillendiği düşünüldüğünde yine konum açısından yapıların iyi bir seçime sahip oldukları tespit edilebilir. Ayrıca yapıların kale kapısına yakın olması da ticaret yoluna yakınlık düşünüldüğünde ulaşıma erişim kriteri bakımından da başarılı bir konuma sahip olduklarını kanıtlamaktadır. Kent içerisinde toplumdaki bireylerin tamamının kentsel olanaklara erişimlerinin desteklenmesi gerektiği düşünüldüğünde (Çorbacı ve ark., 2020) konutların yerleşimlerinin iyi bir konuma sahip olduğu söylenebilir.

Yapılar, sürdürülebilir alanlar ana başlığı çerçevesinde değerlendirildiğinde; genel olarak, olumsuz değerlerde olduğu ve bu alandaki kriterleri karşılamadıkları görülmüştür. Isı adası azaltımı kriteri kapsamında değerlendirilen; 2,3,4 ve 5 numaralı yapıların birbirine çok yakın konumlanmış olmaları sebebi ile bölgenin ısı adası etkisini arttırdığı görülmektedir. Bununla birlikte; 1 ve 6 numaralı yapılar, arazide daha uzak/ayrık şekilde kurgulanmıştır. Bu sebepten dolayı 1 ve 6 numaralı yapıların ise; ısı adasını azaltan bir şekilde arazide konumlandıklarını söylemek mümkündür. Isı adasını arttıran konumlamaya sahip dört yapının (Yapı 2, 3, 4 ve 5) bu özellikleri, uzun ve soğuk geçen bir kış iklimine sahip olan Erzurum kenti için olumlu görülmekle birlikte; yaz dönemleri içinse, olumsuz bir etki oluşturmasına neden olmaktadır.

Tablo 5. Çalışmada yer alan geleneksel konutlara ait sürdürülebilirlik değerlendirmesi

Ana Başlıklar	Kriterler	Yapı 1	2	3	4	5	6
Konum ve Ulaşım	Taşkın yatağından kaçınma	+	+	+	+	+	+
	Alan seçimi	+	+	+	+	+	+
	Kompakt gelişim	+	+	+	+	+	+
	Toplumsal kaynaklar	+	+	+	+	+	+
	Ulaşıma erişim	+	+	+	+	+	+
Sürdürülebilir Alanlar	Isı adası azaltımı	+	-	-	-	-	+
	Yağmur suyu yönetimi	-	-	-	-	-	-
Enerji ve Atmosfer	Soğutucu yönetimi	+	+	+	+	+	+
Malzeme ve Kaynaklar	Dayanıklılık yönetimi doğrulaması	+	+	+	+	+	+
	Çevresel açıdan tercih edilebilir ürünler	+	+	+	+	+	+
	Malzeme verimli taşıyıcı sistem	-	-	-	-	-	-
İç Ortam Kalitesi	Havalandırma	+	+	+	+	+	+
	Düşük emisyonlu ürünler	⊥	⊥	⊥	⊥	⊥	⊥

Yağmur suyu yönetimi, sürdürülebilir alanlar ana başlığı altında yer alan bir diğer kriterdir. Bu kriter kapsamında değerlendirilen yapıların hiçbirinde yağmur suyunun toplanarak kullanımına yönelik bir tasarım gerçekleştirilmediği görülmüştür.

Yapılarda kullanılan kalın taş duvarlar, ısı geçişini azaltacak şekilde kurgulanmıştır. Bu durum; yazları ve kışları konutların iç kısımlarının dış ortamdan izole edilmesine imkân sağlamaktadır. Ayrıca, çok sayıda pencereye sahip cephe kurgularından dolayı gerektiği zaman doğal havalandırma ile evlerin uygun bir biçimde iklimlendirilmesinin yapılabildiği gözlemlenmiştir. Bu sebeplerle, konutların tamamının enerji ve atmosfer ana başlığında yer alan kritere uygun olarak tasarlandıkları söylenebilir.

Malzeme ve kaynaklar ana başlığı altında incelenen dayanıklılık yönetimi doğrulaması; binaların taş yapılar olması ve günümüze kadar gelmiş olmaları gibi sebepler

ile olumlu değerlendirilmiştir. Bunun yanı sıra, geleneksel yapıların neredeyse tamamında tercih edilen yerel malzeme kullanımının çalışmada irdelenen tüm yapılarda da tercih edildiği görülmüştür. Fakat, yapıların yığma yapılar olması; duvarların tamamının olması gerekenden çok daha kalın inşa edilmeleri fazla malzeme kullanımına neden olmuştur. Bu nedenle, yapılarda malzeme verimli taşıyıcı sisteminin uygulandığının sürdürülebilirlik açısından söylenmesi mümkün görünmemektedir.

Çalışmada ele alınan geleneksel konut yapıları, iç ortam kalitesi ana başlığı altında irdelendiğinde; soğutucu yönetimi kriteri ile de bahsedilen, cephede yeterli pencere miktarlarına sahip oluşuyla doğal havalandırma açısından uygun tasarımlara sahip olduğu başka çalışmalarda irdelenen farklı türdeki geleneksel yapılarda olduğu gibi (Kartal ve Turcan, 2018) görülmektedir. Bunun yanında; yapılarda genel olarak düşük emisyonlu malzemeler kullanılmakla birlikte, demir gibi çevresel etki açısından diğer doğal ürünlere göre daha fazla olan malzemelerin (Sipahi ve Kulözü-Uzunboy, 2021) de kullanıldıkları görülmüştür.

Elde edilen tüm veriler ışığında tasarımlar irdelenecek olursa, yapıların konum ve ulaşım anlamında en verimli şekilde konumlandırıldıkları gözlenmektedir. Konutların alan seçiminde; doğal afetlerden kaçınıldığı, kompakt gelişimin sağlanmasına yönelik yerleşim sağlandığı, güvenlik ve toplumsal kaynaklardan yararlanılmasına yönelik kolay ulaşılabilir şekilde oluşturulduğu söylenebilir. Sürdürülebilir alan kullanımı ve sürdürülebilir alan yönetiminin çok fazla düşünülmediği, hatta göz ardı edildiği görülebilir. Yapım tarihleri sebebi ile yapılarda özellikle yağmur suyu kullanımına yönelik bir çalışmanın olmayışı da bir eksiklik olarak göze çarpmaktadır.

Enerji ve atmosfer bakımından binaların doğa ile uyumlu ve bu anlamda sürdürülebilir tasarımlar oldukları söylenebilir. Kullanılan taşıyıcı sistem teknolojisi ise, kaynak kullanımında fazla malzeme gerektirmiştir. Günümüze kadar ulaşan doğallığının yanı sıra sağlamlığı ile de dikkat çeken yapılardaki taş kullanımı, sürdürülebilir bir seçim olarak geleneksel konut tasarımlarında dikkat çekmektedir. Yine, başta taş malzeme olmak üzere; yapılarda kullanılan malzemelerin yerel malzemeler olması da yapının genel anlamda malzeme ve kaynak kullanımı açılarından yapıların sürdürülebilir olmasına katkıda bulunmaktadır. İç ortam hava kalitesinin doğal havalandırma ile yeterli düzeyde sağlandığı bu yapılarda, genel olarak düşük karbon emisyonlu ürünler kullanılmış; ancak, demir malzeme kullanımı ile düşük emisyonlu ürün kullanımında bir eksiklik görülmüştür. Bununla birlikte, iç ortam kalitesi bakımından da çalışmada ele alınan yapıların sürdürülebilir olduklarını söylemek de mümkündür.

4. Sonuç

Geleneksel binaların "Leed v4.1 Residential: Single Family" kriterleri üzerinden yeniden oluşturulan kriterlere göre sürdürülebilirliklerinin değerlendirildiği bu çalışmada, çalışmada ele alınan altı geleneksel konut yapısının bu kriterlere genel olarak uygun oldukları görülmüştür. Yapıların değerlendirildiği, "konum ve ulaşım" ile "enerji ve atmosfer" alanlarında oldukça başarılı oldukları; "malzeme ve kaynaklar" ile "iç ortam kalitesi" alanlarında ise, çoğunlukla başarılı oldukları görülmüştür. Sürdürebilir alanlara ait kriterlerde ise, yapıların genel olarak başarısız oldukları söylenebilir. Bu kriterlerin, günümüzde inşa edilen geleneksel yapılara uygulanması, yapıların çevresel ve ekonomik açıdan sürdürülebilirliğine katkıda bulunacaktır.

Örneklem yapılarında değerlendirilen bu kriterler dışında; yapıldığı tarihte kullanılmayan ve bu nedenle de çalışma kapsamı dışında bırakılan elektrik, su, yapay aydınlatma ve iklimlendirme uygulamaları günümüz yapıların sürdürülebilirliklerini olumsuz yönde etkileyen faktörlerdir. Bu nedenle, belirtilen faktörlerin geleneksel yapılara uygulanması esnasında sürdürülebilirlik faktörünün gözetilmesi geleneksel yapılarının doğal özelliği olan sürdürülebilirliklerinin korunumu açısından son derece önemlidir.

Sonuç olarak, geleneksel konut yapılarının doğaları gereği sürdürülebilir oldukları yapılan çalışma ile tespit edilmiştir. Ancak, geleneksel yapılarda kullanılan tasarım bakışı ile günümüz modern yaşamının ihtiyaçları olan elektrik, su, yapay aydınlatma ve iklimlendirme gibi unsurlar, yeni inşa edilecek tasarımlarda sürdürülebilirliğin sağlanması açısından birbirlerine entegre edilmelidir. Bu şekilde bir entegrasyon, restore edilen geleneksel konutların çevresel sürdürülebilirliklerini koruyacaktır. Ayrıca, konut yapılarının geleneksel yapım tekniklerinin geliştirilip günümüz teknolojisi ile entegre bir biçimde uygulanması; yapı türü olarak sayısal üstünlüğe sahip konutların (Sipahi ve Kulözü-Uzunboy, 2021) yapı sektörünün çevreye olan etkisini olumlu yönde etkileyecektir. Böylece; geleneksel konut anlayışının sürdürülebilir bir biçimde modernize edilmesi, kullanıcının tasarımcı ve konut üreticisi iş birliği sayesinde modernize edilen geleneksel konutlara yönlendirilmesinin sağlanması ile bina sektörünün çevreye olan etkilerinin azaltılarak sürdürülebilir hale dönüşmesi, gelecek nesiller için daha yaşanılabilir bir çevre oluşturulmasında yardımcı olacaktır.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	Ç.U.	S.S.
K	50	50
T	50	50
Y	50	50
VTI	50	50
VAY	50	50
KT	50	50
YZ	50	50
KI	50	50
GR	50	50
PY	50	50
FA	-	-

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon, PY= proje yönetimi, FA= fon alımı.

Çatışma Beyanı

Yazarlar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedirler.

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THE USE AND DEVELOPMENT OF ARTIFICIAL INTELLIGENCE IN ARCHITECTURAL DESIGN PROCESSES

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Abstract: Artificial intelligence is widely used as an interactive technology in various professional disciplines. The widespread use of these technologies, which we benefit from in most areas of our lives, in the education sector will provide important developments in the field of education. The main purpose of this study is to analyze the existing studies in which the use of artificial intelligence helps in architectural design processes. In the study, identification, screening, eligibility, inclusion, and data analysis processes were carried out in three search engines such as Web of Science, ScienceDirect, and ULAKBIM. While reporting the research, 'Systematic Literature Review' and 'Preferred Reporting Items for Meta-Analysis' protocols were followed and a total of 35 relevant articles were identified. In the research, three popular Artificial Intelligence applications used in architectural design processes were identified as Generative Adversarial Networks (GAN), Machine Learning, and Data Mining. In addition, Systematic Literature Review (SLR) outputs show that most researchers are supported by artificial intelligence applications in architectural design processes. As a result of the research, it was determined that artificial intelligence is widely used in architectural design processes, however, it has positive effects in 3D and animation parts.

Keywords: Artificial intelligence, Architectural design processes, Landscape architect

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1. Introduction

Today, artificial intelligence applications offer the ability to quickly and efficiently analyze the relationships between complex problems that require high computational power, thereby enabling the development of various strategies for the future. Due to these features, artificial intelligence applications are considered fundamental tools in many disciplines (Figure 1). Through various devices and applications, these technologies serve humanity in many fields. Examples of artificial intelligence technologies include chatbots, virtual assistants like Siri, Alexa, Google AI, and autonomous cars. Despite their widespread use in daily life, it can be said that the number of people who understand the applications and concepts behind artificial intelligence technologies is deficient. The widespread use of these technologies, which we benefit from in many areas of our lives, has led to significant advancements in the education sector (Tazefidan et al., 2022)

According to Teymur and Aytaç Dural (1998), "Design is highly variable, multi-given, multi-faceted, multi-subjective, and therefore multi-disciplinary and multi-contextual." Due to the multifaceted nature of design, design-focused paradigms have begun to be developed.

In the field of design, designers often rely on their own experiences to solve the problems they encounter throughout the design process, and when they feel inadequate, they seek expert opinions to find solutions. This process can lead to a waste of time, as well as result in faulty decisions due to various shortcomings. However, a well-designed artificial intelligence application can significantly contribute to both speeding up the process and making healthier decisions for the future. With the developing world, it can be seen that the concept and field of design are becoming increasingly complex. Although there are countless indicators of design, it is quite difficult to define its boundaries. It is possible to see design in every area and every detail of life. However, it is difficult to define the boundaries of design. In this case, the question of what art is or is not may also bring along an approach to what design is or is not (Akdemir, 2017).

The use of artificial intelligence techniques in architectural design processes is not limited to accelerating thinking and reasoning processes; it also significantly contributes to the learning of various types and amounts of information that are desired to be achieved Austin et al. (1999). Methods such as machine learning and data mining, considered subfields of artificial intelligence, have paved the way for the emergence of the concept of big data, alongside the increase in computational power of computers and advancements in storage capacity.

Figure 1. Areas of application where AI methods are available (Tazefidan et al., 2022).

These methods have contributed to the formation of self-learning systems through algorithms developed by utilizing this data. Today, especially in fields such as computer science, engineering, medicine, and statistics, studies have popularized the use of these techniques in solving many problems and have enabled the discovery of new methods. In the international literature, over the past five years, the number of studies encompassing artificial intelligence-based applications such as data mining, image processing, machine learning, and fuzzy logic has been rapidly increasing across all disciplines. This trend is also clearly observed in the statistics obtained from the Web of Science, SinceDirect, and ULAKBİM databases in Table 4. the developments in artificial intelligence technologies have raised concerns that the need for human labor will decrease across many disciplines, leading to negative scenarios such as unemployment. Similar concerns are being expressed in the field of architecture, with suggestions that artificial intelligence (AI) could displace designers and architects from their jobs (Karslı, 2019).

However, AI and smart algorithms provide significant contributions across a wide range of areas, from generating building forms and plans to calculating construction costs, and from producing facade designs to making structural system decisions, thanks to the various solution alternatives they offer to designers. For example, AI can design facades using image processing methods and classify complex urban data with data mining techniques (Sönmez et al., 2018; Chaillou, 2019; Bingöl et al., 2020; Adem and Çağdaş, 2020). Additionally, machine learning methods allow for the creation of more user-friendly and effective architectural designs by analyzing user experience data (Şapcı and Taşlı Pektaş, 2021).

In this context, it is understood that AI applications play a significant supportive role in design processes, rather than completely sidelining human labor, and offer innovative approaches to solving design problems. It is observed that AI is positioned as a supportive tool for human creativity in creative disciplines such as architecture, thus enhancing human labor rather than replacing it, making it more efficient and effective. This situation suggests that AI can be seen as an element that will empower human designers in the field of architecture, rather than posing a threat to them in the future (Deveci, 2022).

In his work titled "Age of Design," Conklin (2001) argues that we are in a transition period from the age of science to the age of design. Conklin argues that for the past two centuries, we have focused on explaining the natural world through science and that we process and transform these explanations with technology, thus clearly living in a scientific era. However, it argues that the problems of time cannot be solved with scientific facts, definitions, and perceptions.

Hobday et al. (2012) argued for a reevaluation of the widespread applications of design theories, such as those of Hatchuel, and their relationships with the economy and innovation.

The stages of architectural action that can be traditionally defined consist of four phases: decision, design, implementation, and usage. One of these stages, design is a creative process carried out to find a solution to a specific need or problem. In this process, an objective and aesthetic formation emerges as a result of the interaction between sensory and mental information.

Design encompasses the transformation of ideas into a tangible product, structure, or system, taking into account criteria such as aesthetics, functionality, ergonomics, and innovation (Akdemir, 2017).

Predictions regarding architectural design processes are defined as challenging decision-making processes. In these complex problem areas where uncertain information is present, landscape architects increasingly need to adopt different methods from traditional design approaches to make quick decisions with a low error rate and to adapt to the dynamic changes in the parameters of the design problem.

The literature reviews on the subject are as follows;

The advancements in technology, the increase in environmental concerns, and the growing demand for speed driven by a fluctuating economy are leading to an increase in uncertainty and the expectations and requirements from designs are rapidly diversifying. Artificial intelligence programs can combine spatial and attribute information in such an environment, utilizing multiple spatial criteria to present the most suitable options for design.

AI provides countless benefits in architectural design decision support systems, design models (Bozdemir and Mendi, 2005; Jaihar et al., 2020; Rego et al., 2018), smart spaces (Mueller and Ochsendorf, 2015; Bozdemir, 2017), environmentally sensitive structures (Güneş et al., 2016; Tushar et al., 2018), and product selections (Jin et al., 2016; Ding et al., 2007; Ireland and Liu, 2018; Matić et al., 2019).

The use of AI in these areas provides significant contributions to supporting design decisions, ensuring energy efficiency, developing sustainable architectural solutions, and creating user-centered spaces. In particular, AI technologies provide significant advantages in areas such as environmentally friendly structures and smart spaces by optimizing energy consumption and minimizing environmental impacts (Baydoğan, 2013). In this context, AI technologies can process data from different disciplines using big data analysis and machine learning techniques, contributing to better design decisions.

Focusing on methodology in design research has become a priority to develop solution mechanisms for increasingly complex design problems. Studies that seek answers to the questions of how knowledge is created, used, and communicated have led to the systematic implementation of decision-making in the design process. These studies have enabled the development of methods that allow for decision-making based on the time and conditions in which the design problem exists. In conclusion, artificial intelligence offers a wide range of benefits for creating decision-support mechanisms in architectural design, developing design models, constructing smart spaces and environmentally sensitive structures, and making informed product choices.

The concept of artificial intelligence was first brought to the forefront at the Dartmouth Conference in 1956 and has been defined as encompassing all human abilities related to thinking, reasoning, perceiving objective realities, and concluding (Moor, 2006). Artificial intelligence refers to the efforts to create computer models that can think like humans, reason, perceive, move, learn, and produce results by utilizing the knowledge and experience they possess to solve problems. In this context, artificial intelligence has begun to play an important role by establishing a rational foundation for solving design problems and enabling more conscious, objective decisions regarding the products presented. The use of computer models, in addition to traditional systems in design, offers suitable solutions through algorithm-based methods for well-defined problems. Additionally, artificial intelligence is applied as expert systems to generate solutions and make recommendations in the resolution of poorly defined design problems and in areas that require specialized knowledge.

In the decision-making stages of architectural designs, various artificial intelligence algorithms such as artificial neural networks, expert systems, genetic algorithms, and fuzzy logic are utilized. Artificial intelligence programs are preferred more in the field of architectural design because they are algorithms that can produce results similar to those in human decision-making processes, unlike classical logic. In this regard, the literature examining traditional decision-making processes and artificial intelligence-based decision-making processes have been reviewed, and compared, and the advantages and disadvantages have been highlighted.

Design can be defined as the process through which something that is planned takes shape in the human mind as a result of various steps. This concept, in terms of its literal meaning, includes elements such as design, planning, shaping, and structuring, but it is difficult to provide a comprehensive definition of this concept. In various studies, design is defined as a solution plan or an idea aimed at addressing any problem (Demirarslan, 2006). In this context, the concept of architectural design is expressed as the determination and documentation of the structure that will fulfill specific functions based on a particular requirement, along with all the elements involved in the design (İzgi, 1999).

Louis Kahn, one of the famous architects of the 20th century (1901-1974), emphasizes with his statement, "Design is the production of form within a system," that the design process involves not only intuition but also a certain order (Conrads, 1991). As many designers have pointed out, the built environment that emerges as a result of the design process takes shape as a sequence in which events are repeated in chronological order, and although the products may differ, the process itself carries certain patterns. The understanding, development, and elimination of randomness in successful design products began with the first studies on the analysis of the design process through the Design Methods Movement. The members of this movement

have tried to examine how the designer thinks and acts by focusing on the organizational structure of the process. Jones (1992), one of the pioneers of the movement stated that there are three fundamental stages in the design process:

- ➢ The "Analysis Stage," where the problem is defined
- ➢ The "Synthesis Stage," where the solution is created
- ➢ The "Evaluation Stage," where the developed solution is determined

These stages can be referred to as a flowchart of the design process, which is noted to be repeated in all design applications (Cooper and Press, 1995).

The concept of design practice has evolved today, and designers no longer just create products; they have begun to design experiences, societies, and systems (Stewart et al., 2011). For this reason, designers are expected to solve complex design problems at a global or local level in a multidisciplinary and collaborative work environment, which requires them to be experts in many areas. As a result, the design discipline has become a multidisciplinary field, with designers starting to play a mediating and facilitating role among other disciplines (Trummer and Lleras, 2012). This situation has led to the collaboration of design with other disciplines.

Engineering and business have been integrated into design education, and collaborative programs have been established between design and other disciplines. For this reason, there has been an increase in pursuing graduate education in design, particularly in "business and design, design and engineering programs, or integrated undergraduate programs (such as design engineering) (Trummer and Lleras, 2012). For example, Rensselaer Polytechnic Institute (RPI) offers a Bachelor of Science degree in Design, Innovation, and Society (DIS), and Gazi University has an Industrial Design Engineering program, while Özyeğin University offers a graduate program in Design, Technology, and Society. These are a few of the interdisciplinary programs that encompass the field of design.

The interdisciplinary approach becoming a focal point in design education has also been observed in changes within educational institutions. Aalto University was established as Finland's first interdisciplinary university as a result of the merger of the Helsinki School of Economics, Helsinki University of Technology, and The University of Art and Design Helsinki (Restarting Britain Report, 2011). Therefore, interdisciplinary approaches in design education have been framed within the context of creating new programs, renewing curricula, or establishing institutions that provide design education with a different understanding.

The use of artificial intelligence (AI) in solving complex design problems like architecture can be evaluated from various perspectives. AI is a powerful tool for facilitating interaction among different stakeholders in design processes and managing large amounts of interdisciplinary information. For this reason, three research questions are presented below specifically aimed at assisting AI technology in architectural design:

- ➢ What types of Artificial Intelligence (AI) are used in the architectural design process?
- ➢ What types of technology are used in the architectural design process?
- ➢ What are the types of parameters for Artificial Intelligence (AI) in the architectural design process?

2. Materials and Methods

The research method has been determined as a Systematic Literature Review (SLR). The SLR method can be described as a process that, while reviewing the existing literature in a more organized manner employs systematic, transparent, and replicable techniques at every stage to fully explore and evaluate the relevant research (Tang et al., 2011; Munn et al., 2018). A systematic literature review (SLR) validates existing practices, addresses methodological and conceptual differences, identifies emerging trends, explores and encourages future research directions, identifies and analyzes inconsistent findings, and develops recommendations that contribute to decision-making processes (Munn et al., 2018).

This study aims to determine the place of artificial intelligence, whose popularity has increased especially in recent years, in the architectural design literature, analyzes studies found in national and international literature, and systematically reviews existing articles related to the research subjects of Architectural Design and Artificial Intelligence (AI) learning. The current SLR has gathered primary literature by conducting literature reviews of articles published in journals indexed in SCI, SCI-Expanded, SSCI, and AHCI. Additionally, the ScienceDirect website, Web of Science, and ULAKBIM search engines have been identified as the materials for the research. The ScienceDirect website offers features that encourage visitors to explore the universe of scientific articles (Tober, 2011).

After formulating the research questions, keywords to be used in search engines to find relevant journal articles have been determined. To ensure that all relevant articles were included in the data, the query was performed without any time constraints. The appropriate keywords obtained from the title for conducting the review are artificial intelligence, architectural design, landscape design, and artificial intelligence in architectural design. Later, these keyword terms were combined with the Boolean operators "OR" and "AND" to create a search string for use in the definition process, and Table 1 summarizes the literature search plan. To facilitate the extraction of relevant journal articles, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol was implemented by following the flow diagram (Mohamed Shaffril et al., 2021; Ha-Mim et al., 2024).

It is a protocol aimed at explaining the purpose of a research study and summarizing its analytical and methodological strategy before conducting the research (Moher et al., 2015). PRISMA aims to enhance accuracy, and transparency, and reduce reporting errors in systematic review reporting (Liberati et al., 2009). The four stages of the protocol are identification, screening, eligibility, and inclusion.

2.1. Description

Three main search engines were used for scanning the relevant articles: Web of Science, ULAKBIM, and ScienceDirect. These databases offer many options to customize search results. While searching for articles related to the SLR title, the keywords in Table 1 were taken into consideration. At this stage, only keywords have been taken into account to generate search engine results. The first criterion in selecting the articles was the examination of the abstracts. The search results for Web of Science have been identified as 719, while the search results for ScienceDirect have been identified as 2141. A total of 2,860 results need to be examined. However, since the search engine provided a limited number of articles, a snowball strategy was employed to access as many documents as possible (Wohlin et al., 2022).

Table 1. Keywords used for AI application in architectural design

Keywords	Strings and combinations of keywords
Artificial intelligence	Artificial Intelligence or Yapay Zekâ
Landscape Architecture	Landscape Architect or Landscape
Architectural design	Architectural design or Mimari tasarım

2.2. Screening

This stage was carried out by removing duplicates from the results obtained in the identification phase. Out of a total of 2,860 results, 236 findings were identified as duplicates according to the PRISMA protocol technique and were removed (Figure 2).

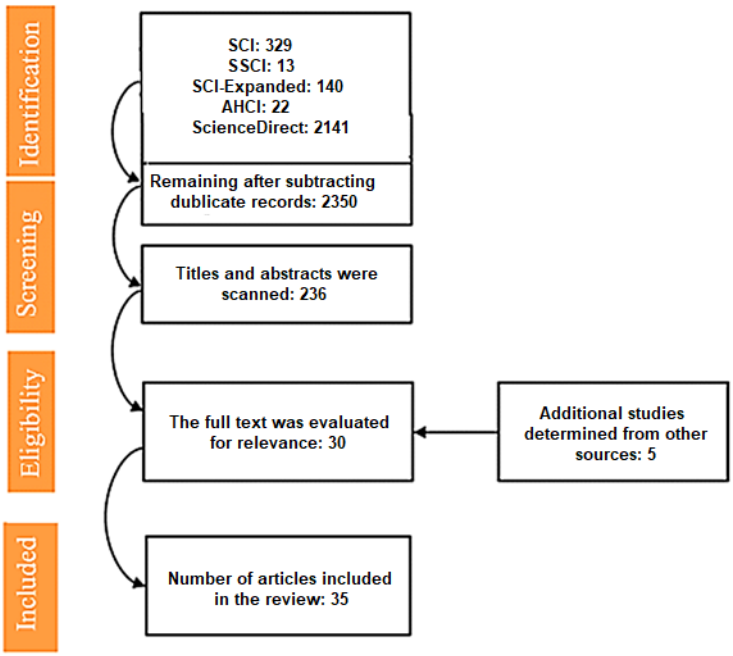

Figure 2. PRISMA protocol.

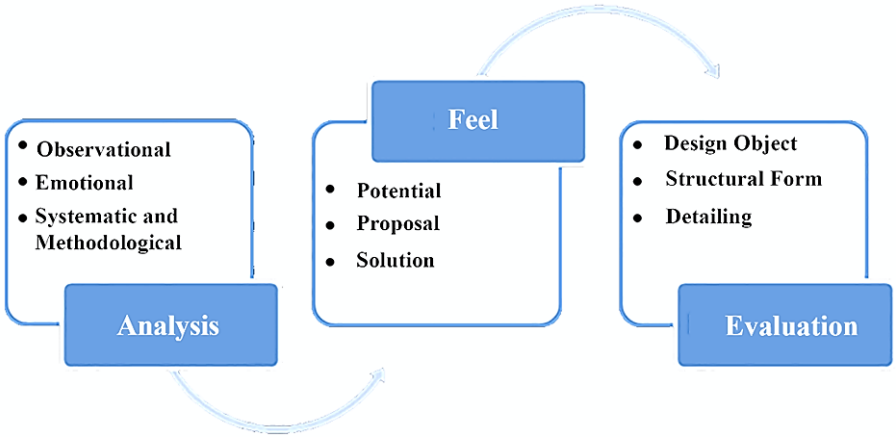

Figure 3. Flowchart of the architectural design process. (Jones, 1992, Baran et al., 2022).

Table 2. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Article title and content	Suitable title and met the requirements of the study	Irrelevant title and did not meet the requirements of the study
Publication Type	Original works and journal articles only	Reviews, editorials, and non-empirical studies
Language	English	Other languages
Article workspace	Architectural design	Fields other than architectural design
Accessibility	Full-text articles	Preview articles and those requiring payment or subscription

The remaining results were then reviewed, and those that did not meet specific criteria such as article title, publication year, document type, language, and accessibility of the articles were excluded. In terms of article titles, they should be related to artificial intelligence in the context of architectural design. Since the chosen topic is related to architectural design, a wider range of fields such as science, technology, engineering, or mathematics has been encountered as the main components of the articles. To ensure that the data is collected from the most recent studies, it has been stipulated that the articles must be published between 2020 and 2024, as artificial intelligence technology is continuously evolving rapidly. In terms of document type, only articles published in academic journals have been selected, while book chapters and conference papers have been excluded. Additionally, the selected articles are written in English, which is a universal language globally recognized as the language of science. Articles published in various languages have also been encountered in the literature. Only articles with full-text access have been selected. Therefore, at this stage, a total of 35 results have been obtained.

2.3. Elimination

This stage was carried out by removing articles that did not meet the criteria from the results obtained in the screening phase. Out of 2,860 results, 295 duplicate findings were identified and removed according to the PRISMA protocol technique (Figure 3). The remaining results were later reviewed, and articles that did not fully meet the requirements based on the article title, publication year, document type, language, and accessibility criteria were excluded. For the titles, it should be related to the use of AI in architectural design. Since the chosen topic is related to architectural design, a broader range has been found among architecture, technology, or design as the main components for the articles. Additionally, due to the rapid and continuous development of AI technology, the articles must have been published between 2020 and 2024 to ensure that the data collected from previous studies is up to date. As a type of document, articles published in scientific journals have been selected, excluding book chapters and conference reviews. In addition, the selected articles are written in English, a universal language, which has allowed access to articles written in various countries. Additionally, only articles with full-text access have been selected. The evaluation process has been carried out for all three search engines used. For this reason, a total of 2409 results have been eliminated at this stage.

2.4. Inclusion

During the process of scanning the full texts of the studies, a technique called backward and forward citation tracking was used, which led to the discovery of 8 additional relevant studies. These eight studies have been found relevant and have been added to the currently established pool of 35 studies. The data sources have been collected through secondary data sources. Examples of secondary data sources include journals, books, documents, reports, and similar items. Journal articles have been chosen as the data source for this SLR. The reason for this is that journals provide a more up-to-date perspective compared to other sources and therefore serve as a reliable source of information. Figure 3 summarizes the inclusion and exclusion criteria.

2.5. Data Analysis

To complete the literature review, relevant findings and information obtained from previous studies were collected and utilized to answer the research question. This review aims to combine and connect the findings of numerous articles, as well as to seek methods for advancing previous research. The inter-rater agreement was evaluated for the excellent coding of the reviewed articles to further support the validity of this SLR. Additionally, thematic analysis has been conducted; this is a technique for identifying patterns or themes in qualitative data. (Nowell et al., 2017). The Included studies have been sorted before being added to the total of 35 publications from which the data were selected. Research articles published in various parts of the world have been gathered to gain a broad perspective. Additionally, all summary sections such as the introduction, methods, results, and discussion have been carefully examined to obtain the desired information to answer the research questions. Such results have been labeled as qualitative data used in this SLR to evaluate summaries and explanations. Later, to validate the current study's validity, two separate authors categorized the themes by classifying them according to their partnerships or interests. A total of 35 articles related to the research were read, and three main categories were identified, followed by a coding process. These categories have been defined as types of artificial intelligence, the technology used, and enhanced parameters (Table 2).

3. Results

Architectural design is a dynamic discipline that continuously evolves and adapts to contemporary approaches, thanks to its deep-rooted traditions, diverse design methods, and the wealth of knowledge accumulated over the years. This flexibility also allows the design to be influenced by technological advancements. Artificial intelligence applications that model human behavior are increasingly offering new technologies that enhance, facilitate, and transform quality of life. The ability of artificial intelligence to quickly analyze complex design problems that require high computational power and to provide future solution alternatives makes significant contributions to the field of architecture. In this context, this study aims to provide a literature-based general review of artificial intelligence-based solutions in architectural fields and applications.

In the methodology section of the study, all scientific works focusing on the concepts of artificial intelligence, architectural design, and landscape architecture were obtained through a literature review method by scanning the designated databases. These studies have been classified into two different categories based on whether the topics examined are directly included in the title or addressed within the content of the study, and they are presented in Table 2 and Table 3. The purpose of creating these tables is to quantitatively highlight the importance of the concept of artificial intelligence in scientific studies conducted over the past five years. Table 2 presents the thesis studies conducted in the last five years regarding the use of artificial intelligence in the context of architectural design in Türkiye. These theses are categorized according to their objectives, based on the contributions and suggestions that artificial intelligence provides in solving structural design problems and addressing issues encountered in the architectural design process. Table 3 lists the studies categorized under artificial intelligence in architectural design within the Web of Science database.

Table 3. Categories of research questions

Research Question	Category
What are the types of Artificial Intelligence (AI) used in the architectural design process?	• Generative Design • Machine Learning • Neural Networks • Natural Language Processing • Computer Vision • Robotic Process Automation (RPA)
What are the types of technology used in the architectural design process?	• Computer Aided Design (CAD) • Building Information Modelling (BIM) • Rendering and Visualisation Technologies • Virtual Reality (VR) and Augmented Reality (AR) • 3D Printers • Artificial Intelligence (AI) and Machine Learning • Photogrammetry and Lidar Scanning • Cloud Based Collaboration Platforms • Drone Technology
What are the types of Artificial Intelligence (AI) parameters in the architectural design process?	• Design Parameters • User Experience Parameters • Performance Parameters • Cost Parameters • Environmental Parameters • Optimisation Parameters • Design Automation Parameters

3.1. Descriptive Results

Figure 4 shows the prevalence of AI topics related to architectural design as extracted from the literature. In this study, the researchers categorized AI topics into 11 different areas: Artificial Neural Networks (ANN), Game Theory and Simulation, Data Mining, Genetic Algorithms, Intelligent Systems, Image Processing, Deep Learning, Machine Learning, Generative Adversarial Networks (GAN), Natural Language Processing (NLP), and Project-Based Learning (PBL). Among the studies related to AI, GAN emerges as the most frequently studied topic (N=19 or 45%). Later, Data Mining (N=5 or 12%), followed by Machine Learning (N=4 or 10%), Image Processing (N=3 or 7%), Artificial Neural Networks (ANN) (N=3 or 7%), and Deep Learning (N=2 or 5%) come next. Finally, only a few studies have been conducted in the fields of Game Theory and Simulation, Intelligent Systems, and Genetic Algorithms with ANN, NLP, and PBL (N=1 or 2%). Image processing is another field of artificial intelligence that helps computers identify objects in videos or images, aiding in the perception of these objects.

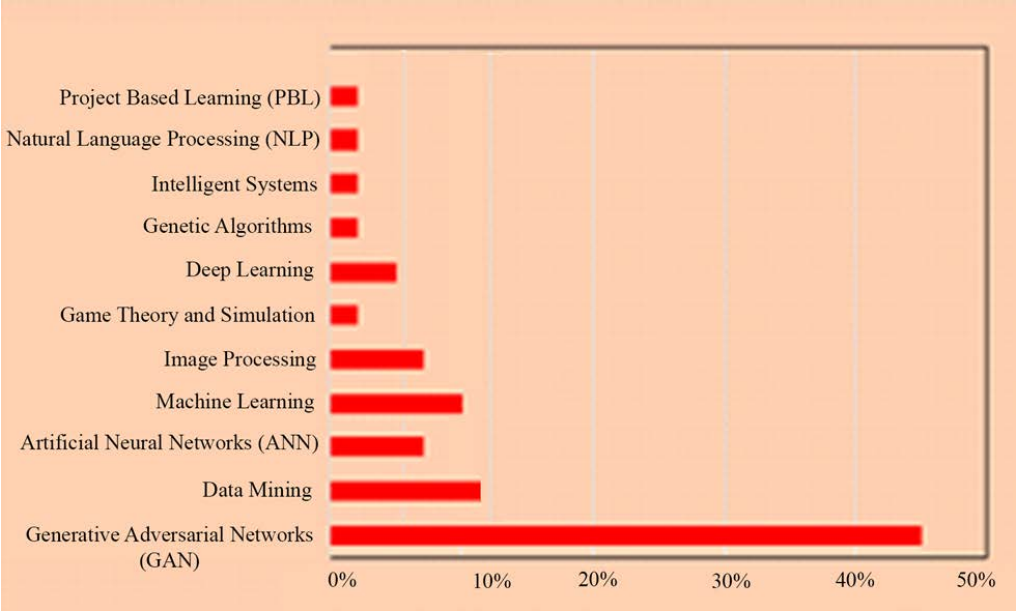

Figure 4. Distribution of AI topics.

This method aims to understand and interpret visual data by mimicking how humans perceive it. Image processing is widely used in various fields such as security, the military industry, medicine, robotics, art, and remote sensing. On the other hand, fuzzy logic is a field of artificial intelligence that aims to think like humans and process these thought processes by converting them into mathematical functions.

Fuzzy logic is a method that combines decision-making processes based on situations where clear predictions are not possible and where different aspects infringe upon each other's boundaries with artificial intelligence. This method aims to transform raw data in large datasets into meaningful insights and informed decisions. The integrating algorithm-based approaches from these artificial intelligence applications into architectural design processes will significantly enhance the analysis of data with intensity, diversity, and scale that designers may find challenging (Çeliker et al., 2020)

3.2. Types of AI Used in the Architectural Design Process

The distribution of articles according to the types of AI applied in the research is shown in Table 4. the table shows that 45% of the articles use Generative Adversarial Networks, indicating that designers are utilizing AI technology primarily for architectural rendering and to quickly present multiple design variations. Such AI applications are generally used to help the user save time and generate suggestions for the designer with a multitude of design options.

11 studies (31%) have used GAN; this means that the program used by the producer to generate more realistic images is directly related to the design of a model or algorithm, along with its own characteristics and technical knowledge. 5 articles (%15) have used Machine Learning; this means that these studies indicate the user's ability to prefer AI technology in terms of material selection and energy efficiency. This type of AI typically uses Decision Trees and Support Vector Machine (SVM) technologies. Five articles (15%) have utilized Data Mining with AI; this means that these studies have employed AI technology in topics such as Urban Planning and Building Placement.

This type of AI typically uses data analysis tools and clustering algorithm technologies. The remaining articles utilized additional artificial intelligence (AI) technologies represented by smaller percentages in the table: Artificial Neural Networks (12%), Image Processing (9%), Intelligent Systems (6%), project-based learning (3%), Game Theory and Simulation (3%), Genetic Algorithms (3%), Deep Learning and Natural Language Processing (NLP) (3%). Figure 4 shows the types of artificial intelligence used in design processes.

3.3. Types of Technology Used in the Architectural Design Process

These studies are very powerful and creative models capable of producing realistic data. This model uses AI technologies for image synthesis and enhancement. According to Table 4, 31% of the studies (11) used competitive producer network-based AI technology. This means that AI can quickly create architectural renderings and design variations in a computer environment using this method. 15% of the studies (5) used Support Vector Machines; this means that these studies made material selections and ensured energy efficiency. Support Vector Machines, characterized by a supervised architecture, are powerful classification and regression method. 15% of the studies (5) used data analysis tools or clustering algorithms; this is the task of obtaining useful data sets from large-scale data and ensuring their security. It is also recognized as part of the information discovery process. It can also be defined as the search for relationships that enable us to make predictions using computer programs within large data sets.

Table 4. AI summary

No.	Yazar	AI Türleri	Kullanılan Teknoloji Türleri	Parametre Türleri
1	Kumar et al. (2024)	Machine Learning	Decision trees, Support Vector Machines (SVM)	Material selection, energy efficiency, project forecast
2	Amer (2023)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
3	Başarır (2021)	Deep Learning	Neural networks, Convolutional Neural Networks (CNN)	Structural analysis, design optimization
4	Bingöl et al. (2020)	Image Processing	Image processing algorithms, camera technologies	Structural analyses, design evaluation
5	Ji and Levinson, (2020).	Game Theory and Simulation	Simulation software, game engines	Architectural design simulations, interactive design
6	Chaillou (2019)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
7	Çeliker et al. (2020)	Image Processing	Image processing algorithms, camera technologies	Structural analyses, design evaluation
8	Demirci and Yabanova (2019)	Image Processing	Image processing algorithms, camera technologies	Structural analyses, 9design e10valuation
9	Deveci (2022)	Machine Learning	Decision trees, Support Vector Machines (SVM)	Mat11erial selection, energy efficiency
10	Deveci(2022).	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
11	Dym (1996)	Artificial Neural Networks (ANN)	Multilayer Perceptron, Recurrent Neural Networks (RNN)	Space analysis, user behavior
12	Kumar et al. (2024)	Intelligent Systems	Rule-based systems, expert systems	Design advice, project management
13	Hayes-Roth (1995)	Intelligent Systems	Rule-based systems, expert systems	Design advice, project management
14	Hornick et al. (2010)	Data Mining	Data analysis tools, clustering algorithms	Urban planning, building layout
15	Karahan et al. (2023)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
16	Kaya and İnce (2012)	Artificial Neural Networks (ANN)	Multilayer Perceptron, Recurrent Neural Networks (RNN)	Space analysis, user behavior
17	Kumar et al. (2023)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
18	Li et al. (2024)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
19	Mirakhorli et al. (2015)	Data Mining	Data analysis tools, clustering algorithms	Urban planning, building layout
20	Płoszaj-Mazurek, et al. (2020)	Machine Learning	Decision trees, Support Vector Machines (SVM)	Material selection, energy efficiency
21	Quan (2022)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
22	Sartipi et al. (2000)	Data Mining	Data analysis tools, clustering algorithms	Urban planning, building layout
23	Shao and Zhang (2018)	Data Mining	Data analysis tools, clustering algorithms	Urban planning, building layout
24	Sohail (2023)	Genetic Algorithms	Genetic algorithms, evolutionary computation	Design optimization, configuration, various design alternatives
25	Şahin (2014)	Artificial Neural Networks (ANN)	Multilayer Perceptron, Recurrent Neural Networks (RNN)	Space analysis, user behavior
26	Şapcı and Pektaş (2021)	Natural Language Processing (NLP)	Language modelling, text analysis	Needs analysis, user feedback 27analysis, de28sign prop29osals
27	Tazefidan et al. (2022)	Machine Learning	Decision trees, Support Vector Machines (SVM)	Material selection, energy efficiency
28	Ünal (2023)	Machine Learning	Decision trees, Support Vector Machines (SVM)	Material selection, energy efficiency
29	Valls et al. (2018)	Data Mining	Data analysis tools, clustering algorithms	Urban planning, building layout
30	Weitz et al. (2021)	Artificial Neural Networks (ANN)	Multilayer Perceptron, Recurrent Neural Networks (RNN)	Space analysis, user behavior, Architectural design modelling, artificial design elements
31	Xi, and Wang (2022).	Project-Based Learning (PBL)	PBLs	User behavior, use of various tools and resources
32	Yıldırım and Demirarslan (2020)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
33	Zeytin et al. (2024)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
34	Zhang et al. (2023)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations
35	Li et al. (2024)	Generative Adversarial Networks (GAN)	GANs	Architectural rendering, design variations

12% of the studies (4) used Multilayer Perceptron technology, which is a type of Artificial Neural Network (ANN) AI. This structure is a mathematical model that attempts to mimic the way the human brain processes information and consists of artificial neurons that work together to solve a problem. This allows for spatial analysis and the examination of user behavior. 9% of the studies (3) used image processing algorithms and camera technologies powered by AI; this is a field of computer science focused on enabling computers to identify and understand objects and people in images and videos. Like other types of artificial intelligence, image processing algorithms also aim to perform and automate tasks that replicate human abilities. Other AI technologies were also included in the reported studies, such as simulation software, support vector machines (SVM), language modeling, and the use of PBL, with each being reported in only one study. Figure 5 shows the types of technology used in the architectural design process.

3.4. Types of AI Parameters in the Architectural Design Process

According to Table 4, 46% of the studies (15 studies) utilized architectural rendering and design variations, indicating that these studies employed AI technology that involves the integration of virtual images into the real world. 15% of the studies (5 studies) utilized 3D technology, and it is understood that these studies involved the overlay of virtual 3D objects or scenes onto the real project. 15% of the studies (5 studies) used a combination of images, 3D models, and animation clips, while the other 6% (2 studies) utilized a combination of video, images, 3D models, and scenes. This shows that these studies involve the layering of various types of visual media in the designed project. Other types of visual media have been reported in the remaining studies; these include the use of video and images (5 studies), objects that alter all or part of an image (1 study), animation clips (1 study), and the use of video (1 study). In general, it is observed that the studies included in the literature review utilize various types of visual media, particularly in AI applications related to 3D models and animation clips, as well as combinations of images, 3D models, animation clips, and videos. Figure 6 shows the types of augmented parameters applied in the architectural design process.

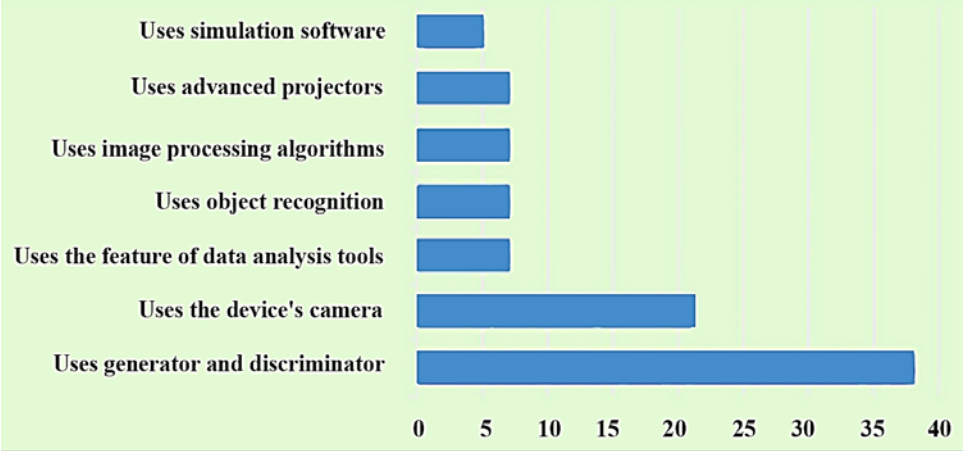

Figure 5. Types of technology used in the architectural design process.

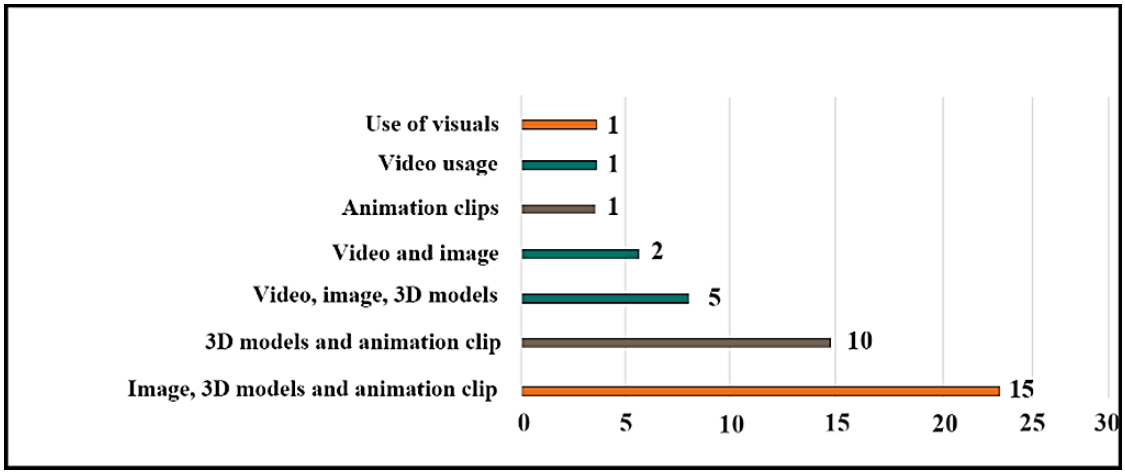

Figure 6. Types of augmented parameters applied in the architectural design process

4. Discussion

Artificial intelligence (AI) technology is advancing rapidly and has recently demonstrated significant potential. The main aim of this study is based on the analysis of existing works that demonstrate how the use of artificial intelligence assists in architectural design processes. In this context, the technologies used, the enhanced parameters, and the application areas have been reviewed.

In a systematic review conducted using three search engines, namely Web of Science, ScienceDirect, and ULAKBIM, a total of 35 articles related to AI in architectural design processes were found. Research results indicate that there are three main types of AI applications used in architectural design processes: Generative Adversarial Networks, Decision Trees, and Data Analysis tools. Generative Adversarial Networks and decision trees are popular in architectural design processes due to their significant advantages. Such AI designs are typically implemented during the 3D phase of the design to make the final version of the project more comprehensible. The generated visuals can convey the visual and auditory content of objects, experiments, and phenomena aiding in the understanding of complex subjects. On the other hand, data analysis tools have a wide capacity due to their advantages, such as demonstrating the possibility of obtaining and extracting valuable data and information to determine the different uses and architectural requirements of an area, including applications like urban planning and building placement. In this context, techniques such as data flow diagrams, design structure matrices, association diagrams, input-process-output diagrams and object-oriented modeling systems are used to provide the advantage of detailing a specific area of the design or modeling data that can be detailed during the design process (Austin et al., 1999; Smith and Jeffrey, 1999). Artificial Neural Networks (ANN) are gaining importance with their spatial analysis, user behavior, architectural design modeling, and wide range of applications. The integration of 3D modeling and animations significantly enhances the interaction and understanding of the parties involved. Using design suggestions with artificial intelligence applications can enhance the design experience by adding digital material to physical design. 3D and animated renders are commonly used components in architectural design. A 3D modeler allows designers to visualize objects and structures in three dimensions, enabling them to observe and manipulate them from various angles.

Animated clips offer the potential to explain complex processes and events that are not easily observable in reality. Device technology positively contributes to architectural design processes, and it is anticipated that the use of AI will be regarded as a fundamental design technology within the next decade. The interactive digital content of AI enhances performance by providing a more meaningful design experience. This situation suggests that artificial intelligence should be included in all design processes. The findings of this systematic literature review (SLR) indicate that the use of AI technologies in architectural design processes can provide significant benefits. For example, it guides designers in selecting the designs they will implement by identifying the AI program suitable for the project, encourages both designers and the commissioning party to overcome the confusion of meaning, and directs more researchers toward AI studies. Additionally, understanding the different classifications and functions of artificial intelligence can help designers choose the best AI variant suited to specific application requirements and create effective AI interactions. Understanding these differences can make it easier to choose the appropriate AI variant for a specific application and to create efficient AI experiences that achieve the intended goals.

The importance of this literature review lies not only in showcasing the existing reviews in AI technology but also in highlighting the types of AI applied in architectural design processes, as well as the research and potential application areas. Findings reveal that there are various fun and useful AI applications are available that will enable designers to create more interactive and innovative designs. Overall, AI is a promising technology in architectural design processes. Architectural rendering and design variations are the most commonly used AI technologies due to their simplicity and effectiveness. Additionally, designers need to understand the differences between the types of AI designs used in education, as this knowledge enables projects to be presented more effectively. Without sufficient knowledge about the types and features of AI, it will not be possible for designers to properly integrate this technology into their projects. Moreover, the findings related to the challenges encountered in architectural design processes with AI encourage improvements in areas where designers can enhance themselves. The main challenges encountered in the application of AI in architectural design processes include dependence on traditional methods, reliance on equipment, insufficient program knowledge, and the lack of awareness of many features of the programs, which leads to their underutilization. However, the use of these technologies is extremely limited, and there is room for their widespread adoption.

In response to the limitations of SLR, other researchers can conduct a more comprehensive literature review by using various database search engines such as ProQuest, Springer, and SCCI. Additionally, more suitable and accurate results can be achieved by using more specific keywords. Future researchers can obtain more comprehensive findings related to AI by examining a broader variety of documents, such as these, dissertations, and conference papers. Regarding paid documents, researchers can use alternative free databases that have been verified and approved by supervisors.

Finally, the current SLR has focused solely on three questions: the types of AI used in architectural design

processes, the types of technologies employed in architectural design processes, and the types of augmented parameters applied in architectural design processes along with the related fields. It might be more interesting to conduct an SLR examining the effects of each technology type on academic performance. Since the current SLR follows the framework of Hajirasouli and Banihashemi (2022), there is a significant need to expand research questions related to the use of AI in architectural design processes.

5. Conclusion

Among the most frequently used artificial intelligence applications, concepts such as machine learning, image processing, data mining and fuzzy logic stand out. When these concepts are briefly examined, machine learning can be defined as a sub-discipline that examines the learning processes of artificial intelligence algorithms and the development of these processes. Systems trained using large data sets are expected to both learn and continuously improve themselves. Machine learning can be used to understand user behavior in architectural projects and to create more user-friendly designs by analyzing how users react to spaces. Machine learning algorithms can also be used to evaluate the performance of different design alternatives. This allows architects to quickly identify the best options.

Data mining is the process of extracting qualitative and useful information from large databases. The main goal of this method is to uncover information that is valuable for decision support mechanisms. By analyzing data from previous projects, data mining can help determine which strategies are more successful in design processes. This information contributes to more efficient planning of new projects. In addition, by analyzing post-project user feedback, insights can be gained on what needs to be improved in future projects.

Nowadays, data mining methods and techniques are widely used in many fields, especially in companies. Image processing can be used to analyze existing structures and determine maintenance requirements. For example, surface cracks or other structural problems can be detected automatically. Image processing techniques enable more realistic visualizations in 3D modeling. This creates an immersive experience during the presentation phase of projects. These points help to better understand the potential of AI in architecture and the innovative solutions it offers. AI plays an important role by making architectural design processes more efficient, sustainable and user-oriented.

Author Contributions

The percentages of the author(s) contributions are presented below. The author(s) reviewed and approved the final version of the manuscript.

	M.D.	M.A.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author(s) declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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ELEKTROMANYETİK DALGALARDAN ENERJİ HASAT ETME TEKNİĞİNE DAYALI İKİ CİHAZA SAHİP ÇİFT YÖNLÜ SİMBİYOTİK AĞ İÇİN KAYNAK TAHSİSİ

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Özet: Altıncı nesil (6G) teknolojisine yön verme potansiyeline sahip nesnelerin interneti (IoT) ağlarının en önemli sorunu cihazların pil ömrüdür. Gelecek nesil haberleşme sistemlerinde kullanılabilecek milyarlarca IoT cihazının pillerini sık sık değiştirmek veya şarj etmek, hem maliyetli hem de zahmetli olduğundan uygulama açısından pratik değildir. Ayrıca bu durum, yüksek bit hızında düşük enerji ve düşük gecikme süresine sahip haberleşme protokolü kurma hedefinden de çok uzaktır. Bu makalede, mevcut sorunun üstesinden gelmek ve bit hızını artırmak için elektromanyetik dalgalardan enerji hasat etme tekniğine dayalı iki kablosuz cihaza sahip çift yönlü simbiyotik bir ağ önerilmiştir. Zaman ve güç açısından cihazlara kaynak tahsisinin yapıldığı bu çalışmada iki farklı senaryo düşünülmüştür. İşbirliksiz senaryoda kablosuz cihazlar kendi haberleşme hedefine ulaşmaya çalışırken, işbirlikli senaryoda ise cihazlar simbiyotik bir ilişki içinde bilgi aktarımını gerçekleştirmektedirler. Önerilen sistemde çift yönlü güç istasyonu (FDPS), iki antene sahip olup hem verici hem alıcı görevi görmektedir. Kablosuz cihazlar tipik sinyal iletimi yapma yeteneğine sahip olmanın yanında, anten yük empedansının değiştirilip anten yansıma katsayısının ayarlanarak bit dizisini elektromanyetik dalga türü olan radyo frekans dalga formlarına eşleme yöntemiyle geri saçılım haberleşme de yapabilmektedir. Kablosuz cihazların hasat ettiği enerjinin miktarına göre çalışma durumlarının belirlendiği bu modelde, matematiksel analizler yapılmış ve her iki model için sistemin objektif fonksiyonu elde edilmiştir. Daha sonra güç ve zaman parametreleri üzerinden kaynak tahsisi yapılarak bit hızı maksimize edilmiştir. Simülasyon sonuçlarında, farklı parametreler üzerinden sistem performansı test edilmiştir. Elde edilen bulgulara göre, FDPS'nin sinyal gücünün düşük olması, uzak cihazın iletişimini ciddi manada etkilemektedir. Ayrıca sistemi çok yüksek frekanslarda kullanmak performansta bir miktar düşüşe sebep olmuştur. Son olarak, işbirlikli senaryonun işbirliksiz senaryoya göre sistem parametrelerinden daha az etkilendiği ve performans açısından daha üstün olduğu grafiksel sonuçlarda gösterilmiştir.

Anahtar kelimeler: 6G teknolojisi, Simbiyotik ağ, Enerji hasadı, Anten yansıma katsayısı, Nesnelerin interneti, Elektromanyetik dalgalar

Resource Allocation for a Full-Duplex Symbiotic Network with two Devices based on the Technique of Harvesting Energy from Electromagnetic Waves

Abstract: The most important problem of IoT networks, which have the potential to drive 6G technology, is the battery life of devices. Frequently changing or charging the batteries of billions of IoT devices that can be used in next-generation communication systems is both costly and inconvenient, making it impractical. Moreover, this is far from the goal of establishing a low energy and low latency communication protocol with high bit rate. In this paper, a full-duplex symbiotic network with two devices based on the technique of harvesting energy from electromagnetic waves is proposed to overcome the existing problem and increase the bit rate. Two different scenarios are considered in this work where resource allocation is determined in terms of time and power. In the non-cooperative scenario, the wireless devices try to reach their own communication destination, while in the cooperative scenario, the devices transfer information in a symbiotic relationship. In the proposed system, the full-duplex power station (FDPS) has two antennas and acts as both a transmitter and a receiver. Wireless devices are not only capable of transmitting a typical signal, but also capable of backscatter communication, which is a method of mapping the bit sequence to radio frequency waveforms, which are a type of electromagnetic wave by changing the antenna load impedance and adjusting the antenna reflection coefficient. In this model, where the operating states of wireless devices are determined according to the amount of energy they harvest, mathematical analysis is performed and the objective function of the system is obtained for both models. Then, the bit rate is maximized by allocating resources over power and time parameters. In the simulation results, the system performance is tested over different parameters. According to the findings, the low signal power of the FDPS seriously affects the communication of the remote device. In addition, using the system at very high frequencies caused some degradation in performance. Finally, the graphical results show that the cooperative scenario is less affected by the system parameters than the non-cooperative scenario and is superior in terms of performance.

Keywords: 6G technology, Symbiotic network, Energy harvesting, Antenna reflection coefficient, Internet of things, Electromagnetic waves

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1. Giriş

6G teknolojisi ile fiziksel ortamlardaki verilerin kablosuz cihazlar tarafından algılanması, izlenmesi, hızlı ve gecikmesiz olarak düşük enerjide alıcı terminale aktarılması işleminin, geliştirilecek yeni haberleşme protokolleri sayesinde mümkün olacağı öngörülmektedir (Wang ve ark., 2023). Örneğin uzak, erişilemez veya tehlikeli bölgelere konumlandırılmış kablosuz cihazlar mevcut sistem gereksinimlerine hizmet verebilir. Ancak bu tip kablosuz cihazlar için maliyet ve güvenlik endişeleri nedeniyle düzenli pil değişimi çok pratik değildir. Bu sebeple, hem gelecek nesil haberleşme sistemleri için sürdürülebilir ağ operasyonları elde etmek hem de enerji tüketimini azaltmak için yeşil iletişimi teşvik edecek yeni yöntemler geliştirildi (Guo ve ark., 2017; Pradhan ve Priyanka, 2020). Radyo dalgalarının elektromanyetik spektrumda en büyük dalga boyuna yani en küçük frekansa sahip elektromanyetik dalga olma özelliği, kablosuz güç transferi yöntemiyle elektromanyetik dalgalardan faydalanılarak enerji hasadı gerçekleştirmenin önünü araştırmacılara açtı (Kang ve ark., 2015, Ullah ve ark., 2024). Bu bağlamda, elektromanyetik dalgalardan enerji hasat etme tekniği, özellikle IoT paradigmasında ve 6G iletişiminde kendi kendini idame ettiren iletişim sistemleri oluşturma potansiyeli nedeniyle oldukça önem kazanmaktadır (Lu ve ark., 2014; Seid ve ark., 2022; Psomas ve ark., 2024). Bu sebeple, gelecekteki IoT ağlarında enerji hasat etme tekniğini etkin bir şekilde kullanmak için, enerji tabanlı verimli iletişim stratejileri dizayn etmek kaçınılmazdır.

Kablosuz ağların yalnızca standart veya programlı iletişim cihazlarına değil, aynı zamanda cihazların birbirleriyle işbirlikçi bir yaklaşımla hareket ettikleri simbiyotik ağlar da bu kapsamda düşünülerek, sistem performansının artırılması beklenmektedir (Mahmood ve ark., 2021; Al-Nahari ve ark., 2023; Janjua ve Arslan, 2023). Ağ kapasitesini en üst düzeye çıkarırken enerji tüketimini en aza indirmek için yeni spektrum yönetim tekniklerinin geliştirilmesine rehberlik edecek simbiyotik ağlar, aynı alıcıya bit iletimi gerçekleştiren ve frekans spektrumunu ortak kullanan cihazlardan oluşur (Long ve ark., 2019a, Yuan ve ark., 2023, Yang ve ark., 2023). Bu cihazlar, simbiyotik ağlarda ortak hareket ederek hem kendi haberleşme hedeflerine ulaşırlar hem de diğer cihazın bit iletimine yardımcı olarak sistem performansını üst seviyelere çıkarırlar (Giordani ve ark., 2020; Ghafoor ve Siddiqui, 2024). Simbiyotik ağda çalışan cihazlar, radyo frekans sinyalinden enerji hasadı yapmanın yanında geri saçılım haberleşme ile de bit aktarımı gerçekleştirebilirler. Yeni nesil iletişim sistemleri için enerji sorununun üstesinden gelme potansiyeline sahip olan geri saçılım haberleşmede, anten yük empedansının değiştirilip anten yansıma katsayısının ayarlanarak bit dizisini elektromanyetik dalga türü olan radyo frekans dalga formlarına eşleme yöntemi kullanılır (Long ve ark., 2019b; Liang ve ark., 2020; Ren ve Liu, 2023). Literatürde yürütülen çalışmalarda mevcut sistemlerde görev alan cihazların geri saçılım haberleşme ve enerji hasadı yapabilmesi, özellikle IoT tabanlı sistem modellerinin performansı açısından ciddi katkı sağlamaktadır. (Onay, 2024a, b).

6G kapsamında yürütülen çalışmaların temelinde sistemin toplam bit hızını artırma hedefi vardır (Onay ve Ertuğ, 2023a). Bu konu kapsamında sunulan protokoller daha çok cihazların işbirliksiz olarak harici bir alıcıya bilgi iletiminde bulunduğu yapılardır. Ayrıca türetilen optimizasyon problemlerinde sadece zaman veya güç kaynak tahsis şemaları ele alınmış ve sistem performansı cihazların hasat ettikleri enerji seviyesi dikkate alınmadan tek kapasite formülü yazılarak bit hızı maksimize edilmiştir (Kang ve ark., 2015; Zhang ve ark., 2019).

Bu makalede, elektromanyetik dalgalardan enerji hasat etme tekniğine dayalı iki cihaza sahip çift yönlü simbiyotik radyo ağı için zaman ve güç açısından kaynak tahsisi birlikte düşünülmüş ve sistemin toplam bit hızı maksimize edilmiştir. Sunulan sistem, IoT tabanlı simbiyotik ağlarda güç istasyonunun çift yönlü düşünülerek hasat edilen enerji seviyesine göre bit hızının maksimize edildiği ilk yaklaşımdır. Önerilen sistem modeli gelecek nesil haberleşme sistemlerinde akıllı şehir uygulamaları kapsamında özellikle veri toplama-izleme-denetleme faaliyetleri açısından değerlendirilebilir. FDPS terminali, Onay ve Ertuğ (2023b) çalışmasından farklı olarak çift yönlü donatılmış alıcı-verici terminalidir. FDPS'den uzak-yakın olacak şekilde konumlandırılmış iki kablosuz cihaz, Yang ve ark. (2023), Ullah ve ark. (2024)'ten farklı olarak hem FDPS sinyalinden enerji hasadı yapabilmekte hem de geri saçılım yoluyla FDPS alıcı antenine bilgi iletebilmektedir. Guo ve ark. (2017) ve Liang ve ark. (2020) senaryolarının aksine, önerilen sistem modelinde işbirlikli ve işbirliksiz senaryolar dikkate alınmış ve simbiyotik ağın performansı değerlendirilmiştir. Bit hızının maksimize edildiği Kang ve ark. (2015) ve Onay (2024) benzer çalışmalarından farklı olarak bu yaklaşımda, enerji seviyesi değişimi ve kullanıcılara tahsis edilecek güç-zaman kaynakları açısından bir optimizasyon problemi türetilmiştir. Son olarak toplam bit hızı değişimi, sistem parametrelerine göre bulunmuş ve grafiksel olarak gösterilmiştir.

Bu makalenin temel katkıları aşağıdaki gibi özetlenebilir:

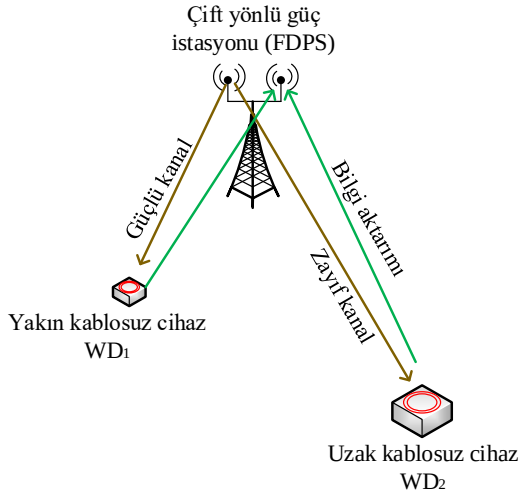
1. Çift yönlü iletişimin temel alındığı IoT tabanlı simbiyotik radyo ağları için önerilen bu sistem, güç tahsis katsayıları ve zaman değişkenlerinin birlikte optimize edilerek enerji hasat etme tekniğine dayalı sistemin toplam bit hızının maksimize edilmeye çalışıldığı ilk yaklaşımdır.
2. Sistem modelindeki cihazların hasat ettiği enerjinin miktarına göre olası tüm kanal kapasitesi ifadeleri yazılmış ve optimizasyon probleminin objektif fonksiyonu değerlendirilmiştir.
3. Önerilen sistemde çift yönlü güç istasyonu (FDPS), iki antene sahip olup hem verici hem alıcı görevi görmektedir.
4. Önerilen modelde iki farklı senaryo düşünülmüştür.

İşbirliksiz senaryoda kablosuz cihazlar kendi haberleşme hedefine ulaşmaya çalışırken, işbirlikli senaryoda ise cihazlar simbiyotik bir ilişki içinde bilgi aktarımını gerçekleştirmektedirler.

5. Simülasyon sonuçlarında, farklı parametreler üzerinden sistem performansı test edilmiştir. Elde edilen bulgulara göre, FDPS'nin sinyal gücünün düşük olması, uzak cihazın iletişimini ciddi manada etkilemektedir. Ayrıca sistemi çok yüksek frekanslarda kullanmak performansta bir miktar düşüşe sebep olmuştur. Son olarak, işbirlikli senaryonun işbirliksiz senaryoya göre sistem parametrelerinden daha az etkilendiği ve performans açısından daha üstün olduğu grafiksel sonuçlarda gösterilmiştir.
6. Önerilen sistem modeli gelecek nesil haberleşme sistemlerinde akıllı şehir uygulamaları kapsamında özellikle veri toplama-izleme-denetleme faaliyetleri açısından değerlendirilebilir.

2. IoT Tabanlı Sistem Modeli

Önerilen sistem modeli Şekil 1'de verilmiştir. İki farklı yere konumlandırılmış IoT cihazları, FDPS ile iletişim halindedir. FDPS, iki anten aracılığıyla tam çift yönlü çalışır: biri aşağı bağlantıdaki cihazlara kablosuz enerji yayını için, diğeri ise yukarı bağlantıda kullanıcılardan eşzamanlı olarak bilgi almak için. Burada FDPS terminalinin sahip olduğu iki anten arasında sinyal girişimi olmadığı kabul edilmiştir. Önerilen haberleşme protokolünde Φ_0 süresince FDPS terminali, her iki cihaza kablosuz olarak enerji aktarımı yapar.



Şekil 1. Önerilen sistem modeli.

FDPS, cihazlar arasındaki kanal sönümleme kazancına göre ilettiği gücü uyarlayabilme yeteneğine sahiptir. Haberleşme kanalı, serbest uzay yol kaybı olarak modellenip terminaller arasında herhangi bir engelin bulunmadığı varsayılmıştır. Terminaller arasındaki kanal kazançları aşağıdaki denklemler ile verilebilir (eşitlik 1-3).

$$g_{P_s-f} = g_{f-P_s} = \frac{G_t G_f \lambda^2}{\left(4\pi d_{f-P_s}\right)^2} \tag{1}$$

$$g_{P_s-n} = g_{n-P_s} = \frac{G_t G_n \lambda^2}{\left(4\pi d_{n-P_s}\right)^2} \tag{2}$$

$$g_{f-n} = \frac{G_f G_n \lambda^2}{\left(4\pi d_{f-n}\right)^2} \tag{3}$$

burada, FDPS-WD_2, FDPS-WD_1 ve WD_1-WD_2 arası kanal kazançları ve mesafeler sırasıyla $g_{f\text{-}Ps}$ ($d_{f\text{-}Ps}$), $g_{n\text{-}Ps}$ ($d_{n\text{-}Ps}$) ve $g_{f\text{-}n}$ ($d_{f\text{-}n}$) olarak verilmiştir. Ayrıca FDPS anten kazancı G_t, WD_1 anten kazancı G_n, WD_2 anten kazancı G_f, sinyal dalga boyu λ ile temsil edilir. Sistem modelinin bit hızı açısından performans analizinin değerlendirilmesi için iki farklı senaryo düşünülmüştür.

2.1. İşbirliksiz Senaryo

Bu senaryoda Φ_1 süresince sadece WD_1 aktiftir. Φ_0 süresince hasat edilen enerji seviyesine göre aktif ya da pasif haberleşme tekniğini uygulayan WD_1, alıcı antene bit iletimini gerçekleştirmektedir. Aynı şekilde WD_2 de, kendisinde depolanan güç seviyesine göre Φ_2 süresince aktif ya da pasif haberleşme yöntemiyle bit iletimini yürütmektedir.

2.1.1. İşbirliksiz senaryoda WD_1 için kanal kapasitesi ve enerji hasat etme protokolü

WD_1 için kanal kapasitesi formülü eşitlik 4'deki gibi yazılabilir.

$$R_n^1 = \begin{cases} \phi_1 \log_2\left(1+\dfrac{P_n g_{n-P_s}}{N_0}\right), & \mathrm{E}_h^n > E_c \text{ ise} \\ \phi_1 \log_2\left(1+\dfrac{P_s \alpha_n \alpha g_{P_s-n} g_{n-P_s}}{N_0}\right), & \mathrm{E}_h^n \le E_c \text{ ise} \end{cases} \tag{4}$$

Eşitlik 4'te, anten yansıma katsayısı α, yakın kablosuz cihaz için güç tahsis katsayısı α_n ($0 < \alpha_n \le 1$), uzak kablosuz cihaz için güç tahsis katsayısı α_f ($0 < \alpha_f \le 1$), FDPS sinyal gücü P_s olarak ifade edilmiştir. Uzak kullanıcıya daha fazla güç tahsis edilmesi gerektiğinden burada $0 < \alpha_n \le \alpha_f \le 1$ dir. Gürültü gücü N_0 olup tüm terminallerde eşit olduğu varsayılmıştır. Enerji hasat etme protokolü için eşitlik 5 ve 6'da verilen denklemler yazılabilir.

$$\mathrm{P}_n = \frac{E_n}{\phi_1} \tag{5}$$

$$\begin{aligned} E_n &= \mathrm{E}_h^n - E_c \\ \mathrm{E}_h^n &= P_s \alpha_n g_{P_s-n} \phi_0 + E_i \end{aligned} \tag{6}$$

burada P_n, WD_1'in aktif bit iletimi sırasında gönderdiği sinyalin gücü, E_h^n, WD_1 tarafından hasat edilen enerji, E_i başlangıç enerjisi, E_c bit iletim sırasında WD_1 tarafından harcanan enerjidir. Eşitlik 4'ten görüleceği üzere WD_1'in aktif bit iletiminde çalışabilmesi için gerekli koşul eşitlik

7'deki gibidir.

$$\mathrm{E}_h^n > E_c \tag{7}$$

Bu koşul sağlanmadığı takdirde WD_1, FDPS'nin sinyalini geri saçarak pasif haberleşme yöntemi ile bilgi aktarımını gerçekleştirir. eşitlik 6, eşitlik 7'de yerine yazılırsa aşağıdaki verilen eşitsizlik (eşitlik 8) elde edilir.

$$\begin{aligned} &P_s\alpha_n g_{P_s-n}\phi_0 + E_i > E_c \\ &1 > \phi_0 > \frac{E_c - E_i}{P_s\alpha_n g_{P_s-n}} \end{aligned} \tag{8}$$

İşbirliksiz senaryo için WD_1'in çalışma durumu Eşitlik 9'daki gibi özetlenebilir.

$$\begin{cases} \text{Aktif haberleşme ile bit iletimi, } 1 > \phi_0 > \dfrac{E_c - E_i}{P_s\alpha_n g_{P_s-n}} \text{ ise} \\ \text{Pasif haberleşme ile bit iletimi, } 0 < \phi_0 < \dfrac{E_c - E_i}{P_s\alpha_n g_{P_s-n}} \text{ ise} \end{cases} \tag{9}$$

2.1.2. İşbirliksiz senaryoda WD_2 için kanal kapasitesi ve enerji hasat etme protokolü

WD_1'e benzer şekilde, WD_2 için kanal kapasitesi formülü eşitlik 10'daki gibi yazılabilir.

$$R_f^1 = \begin{cases} \phi_2 \log_2\left(1 + \dfrac{P_f g_{f-P_s}}{N_0}\right), & \mathrm{E}_h^f > E_c \text{ ise} \\ \phi_2 \log_2\left(1 + \dfrac{P_s\alpha_f\alpha g_{P_s-f} g_{f-P_s}}{N_0}\right), & \mathrm{E}_h^n \le E_c \text{ ise} \end{cases} \tag{10}$$

WD_2 için enerji hasat etme protokolü Eşitlik 11 ve 12'deki gibi yazılabilir.

$$P_f = \frac{E_f}{\phi_2} \tag{11}$$

$$\begin{aligned} E_f &= \mathrm{E}_h^f - E_c \\ \mathrm{E}_h^f &= P_s\alpha_f g_{P_s-f}\phi_0 + E_i \end{aligned} \tag{12}$$

Burada, P_f, WD_2'nin aktif bit iletimi sırasında gönderdiği sinyalin gücü, E_h^f, WD_2 tarafından hasat edilen enerjidir. Eşitlik 10'dan görüleceği üzere WD_2'nin aktif bit iletiminde çalışabilmesi için gerekli koşul aşağıda erilen eşitlik 13 ve 14'deki gibidir.

$$\mathrm{E}_h^f > E_c \tag{13}$$

$$\begin{aligned} &P_s\alpha_f g_{P_s-f}\phi_0 + E_i > E_c \\ &1 > \phi_0 > \frac{E_c - E_i}{P_s\alpha_f g_{P_s-f}} \end{aligned} \tag{14}$$

Sonuç olarak işbirliksiz senaryo için WD_2'nin çalışma durumu eşitlik 15 ve 16'daki gibi özetlenebilir.

$$\begin{cases} \text{Aktif haberleşme ile bit iletimi, } 1 > \phi_0 > \dfrac{E_c - E_i}{P_s\alpha_f g_{P_s-f}} \text{ ise} \\ \text{Pasif haberleşme ile bit iletimi, } 0 < \phi_0 < \dfrac{E_c - E_i}{P_s\alpha_f g_{P_s-f}} \text{ ise} \end{cases} \tag{15, 16}$$

İşbirliksiz senaryo için FDPS'nin alıcı antenine ulaşan toplam bit sayısı, olası tüm durumlar dikkate alınarak denklem 16'daki gibi ifade edilebilir. $E_h^n > E_c$ durumları için ϕ_2 süresince, alıcı anten kısmında WD_1 kaynaklı gürültü mevcuttur. Bunun sebebi, WD_1'in aktif bit iletimi yapmasıyla bir önceki periyottan (ϕ_1 süresi) artık sinyal kalmasıdır. Denklemdeki τ (0< τ <1), sabit bir katsayı olup FDPS'nin alıcı anten tarafındaki kusurlu ardışık girişim giderici katsayısıdır.

2.2. İşbirlikli Senaryo

İşbirliksiz senaryodan farklı olarak Φ_2 süresince WD_1, WD_2'nin rölesi gibi davranarak simbiyotik bir ilişki içinde bit aktarımı gerçekleştirilir.

2.2.1. İşbirlikli senaryoda WD_1 için kanal kapasitesi ve enerji hasat etme protokolü

İşbirliksiz senaryo için yazılan denklem 4'teki R_n^1 ifadesi, işbirlikli senaryoda WD_1'in alıcı antene gönderdiği bit sayısı R_n^2'ye eşittir. Aralarındaki tek fark enerji hasat denklemindedir. İşbirlikli senaryoda WD_1'in hasat ettiği enerji Eşitlik 17'deki denklem ile verilir.

$$\mathrm{E}_h^n = (P_s\alpha_n g_{P_s-n}\phi_0)\gamma + E_i \tag{17}$$

burada γ, güç bölme faktörüdür.

2.2.2. İşbirlikli senaryoda WD_2 için kanal kapasitesi ve enerji hasat etme protokolü

$$R_f^2 = \begin{cases} \phi_2 \log_2\left(1 + \dfrac{P_n^r g_{n-P_s}}{N_0}\right), & \mathrm{E}_n^r > E_c^r \text{ ise} \\ \phi_2 \log_2\left(1 + \dfrac{P_s\alpha_f\alpha g_{P_s-f} g_{f-n} g_{n-P_s}}{N_0}\right), & \mathrm{E}_n^r \le E_c^r \text{ ise} \end{cases} \tag{18}$$

burada E_c^r, WD_1'in ϕ_2 süresince röle olarak kullanımı sırasında harcanan enerjidir. WD_1'in röle olarak kullanımı sırasında gönderdiği sinyalin gücü P_n^r, aşağıda verilen Eşitlik 19-21'deki gibi yazılabilir.

$$P_n^r = P_f g_{f-n} + P_h^n \tag{19}$$

$$P_f = \frac{E_f}{\phi_2} = \frac{P_s\alpha_f g_{P_s-f}\phi_0 + E_i - E_c}{\phi_2} \tag{20}$$

$$P_h^n = \frac{(P_s\alpha_n g_{P_s-n}\phi_0)(1-\gamma) + E_i - E_c}{\phi_2} \tag{21}$$

WD_1 tarafından hasat edilen net enerji (Eşitlik 22),

$$\begin{aligned} E_n^r &= P_n^r\phi_2 \\ &= \left(P_s\alpha_f g_{P_s-f}\phi_0 + E_i - E_c\right) g_{f-n} \\ &\quad + \left((P_s\alpha_n g_{P_s-n}\phi_0)(1-\gamma) + E_i - E_c\right) > E_c^r \end{aligned} \tag{22}$$

ile temsil edilir. WD_1'in WD_2'nin rölesi olarak çalıştığı ϕ_2 süresince çalışma durumları şu şekilde özetlenebilir.

$E_n^r > E_c^r$ ise WD_1, WD_2'nin rölesi olarak çalışır ve bilgiyi aktif olarak FDPS'nin alıcı antenine iletir. $E_n^r \leq E_c^r$ ise WD_1, WD_2'nin yine rölesi olarak çalışır ancak bu sefer bilgiyi pasif olarak FDPS'nin alıcı antenine iletir. Her iki senaryoda da WD_2'nin bit iletiminin WD_1'den sonra olmasının nedeni, daha fazla enerji hasat etmesine imkân sağlamak içindir. İşbirlikli senaryo için FDPS'nin alıcı antenine ulaşan toplam bit sayısı, olası tüm durumlar dikkate alınarak denklem 23'deki gibi ifade edilebilir.

$$R_1 = \begin{cases} \phi_1 \log_2\left(1+\frac{P_n g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_f g_{f-P_s}}{N_0+P_n g_{n-P_s}\tau}\right), & \text{durum 1: } \mathrm{E}_h^n > E_c \text{ ve } \mathrm{E}_h^f > E_c \\ \phi_1 \log_2\left(1+\frac{P_n g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_s \alpha_f \alpha g_{P_s-f} g_{f-P_s}}{N_0+P_n g_{n-P_s}\tau}\right), & \text{durum 2: } \mathrm{E}_h^n > E_c \text{ ve } \mathrm{E}_h^f \leq E_c \\ \phi_1 \log_2\left(1+\frac{P_s \alpha_n \alpha g_{P_s-n} g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_f g_{f-P_s}}{N_0}\right), & \text{durum 3: } \mathrm{E}_h^n \leq E_c \text{ ve } \mathrm{E}_h^f > E_c \\ \phi_1 \log_2\left(1+\frac{P_s \alpha_n \alpha g_{P_s-n} g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_s \alpha_f \alpha g_{P_s-f} g_{f-P_s}}{N_0}\right), & \text{durum 4: } \mathrm{E}_h^n \leq E_c \text{ ve } \mathrm{E}_h^f \leq E_c \end{cases}$$

$$R_2 = \begin{cases} \phi_1 \log_2\left(1+\frac{P_n g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_n^r g_{n-P_s}}{N_0+P_n g_{n-P_s}\tau}\right), & \text{durum 1: } \mathrm{E}_h^n > E_c \text{ ve } \mathrm{E}_n^r > E_c^r \\ \phi_1 \log_2\left(1+\frac{P_n g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_s \alpha_f \alpha g_{P_s-f} g_{f-n} g_{n-P_s}}{N_0+P_n g_{n-P_s}\tau}\right), & \text{durum 2: } \mathrm{E}_h^n > E_c \text{ ve } \mathrm{E}_n^r \leq E_c^r \\ \phi_1 \log_2\left(1+\frac{P_s \alpha_n \alpha g_{P_s-n} g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_n^r g_{n-P_s}}{N_0}\right), & \text{durum 3: } \mathrm{E}_h^n \leq E_c \text{ ve } \mathrm{E}_n^r > E_c^r \\ \phi_1 \log_2\left(1+\frac{P_s \alpha_n \alpha g_{P_s-n} g_{n-P_s}}{N_0}\right)+\phi_2 \log_2\left(1+\frac{P_s \alpha_f \alpha g_{P_s-f} g_{f-n} g_{n-P_s}}{N_0}\right), & \text{durum 4: } \mathrm{E}_h^n \leq E_c \text{ ve } \mathrm{E}_n^r \leq E_c^r \end{cases} \quad (23)$$

Bu makalede amacımız, hem R_1 hem de R_2 'yi ϕ_1, ϕ_2, α_n ve α_f değişkenleri üzerinden maksimize etmektir. Bu noktada problem çözümünde aşağıda verilen eşitsizlikler, her iki senaryo için de kısıt olarak değerlendirilir (Eşitlik 24-30).

$$R_n^1 \geq R_n^+ \quad (24)$$

$$R_f^1, R_f^2 \geq R_f^+ \quad (25)$$

$$0 < \alpha_n \leq \alpha_f \leq 1 \quad (26)$$

$$0 \leq \phi_1, \phi_2 \leq 1 \quad (27)$$

$$0 < \gamma \leq 1 \quad (28)$$

$$0 \leq \tau \leq 1 \quad (29)$$

$$\sum_{i=0}^{2} \phi_i \leq 1 \quad (30)$$

Denklem 24 ve 25, WD_1 ve WD_2'nin hizmet kalitesini (QoS) garanti altına almak için göndermeleri gereken minumum bit sayısını ifade eder. Denklem 26, 27, 28 ve 29, sistem parametrelerinin 1'den büyük ve negatif bir sayı olamayacağını belirtir. Denklem 30, sistem periyodunun 1 saniyeyi geçemeyeceğini ve normalize edildiğini gösterir.

3. Nümerik Analiz ve Tartışma

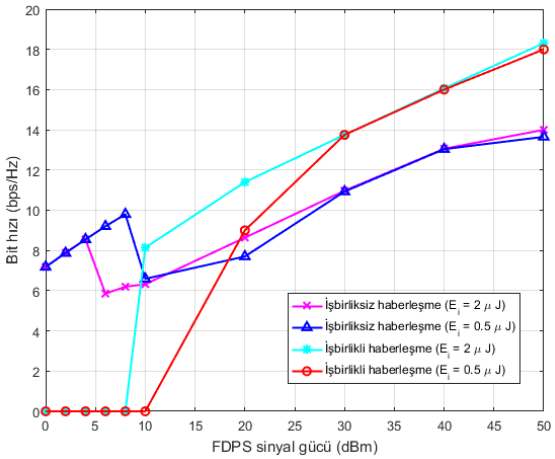
Bu bölümde nümerik analizler yapılmış ve sonuçlar grafiksel olarak gösterilmiştir. Bilgisayar ortamında gerçekleştirilen simülasyonlarda kullanılan parametre değerleri aşağıdaki gibidir: P_S = 30 dBm, α = 0.7, E_c = 3 µJ, E_c^r = 0,1 µJ, N_0 = 10^{-12} W, E_i = 2 µJ, ϕ_0 = 0,2 s, R_n^+ = 3 bps/Hz, R_f^+ = 1 bps/Hz, τ = 0,01, γ = 0,5, $d_{f\text{-}Ps}$ = 3 m, $d_{n\text{-}Ps}$ = 1 m, $d_{f\text{-}n}$ = 2,1 m, G_t = G_f = G_n = 6 dBi, f = 2,4 GHz. Aksi belirtilmediği sürece yukarıda verilen değerler referans alınmıştır.

Şekil 2'de FDPS terminalinin verici anteninden yayılan sinyalin gücüne göre farklı başlangıç enerji seviyeleri altında sistemin ulaşabileceği toplam bit hızı değişimi gösterilmiştir. Grafiğe göre en yüksek bit iletim hızı işbirlikli haberleşme (E_i=2 µJ) için elde edilirken, en düşük bit iletim hızı işbirliksiz haberleşme (E_i =0,5 µJ)'da elde edilmiştir. Tüm senaryolarda kritik noktalarının elde edilmesinin sebebi, hasat edilen enerjiye bağlı olarak denklem 16 ve denklem 23 için verilen durum değişikliklerinin yaşanmasındandır. İşbirliksiz haberleşme (E_i=2 µJ) senaryosunda, P_s = 4 dBm değerinden sonra 6 dBm değerine kadar bit hızında azalış olmasının sebebi, optimizasyon probleminde enerji durum değişikliğidir. P_s= 0, 2, 4 dBm değerlerinde durum 4'te çalışan sistem, P_s=6 dBm değerinden sonra durum 2'ye geçiş yapar. P_s=20 dBm değerinden sonra durum 1'de çalışarak bit iletim hızı artırılır. E_i'nin yüksek olması,

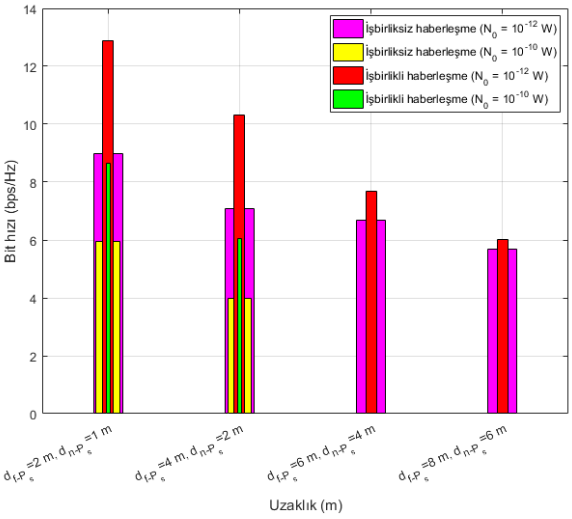
optimizasyon probleminde objektif fonksiyonunun durum 1'de kalmasını sağlayarak P_s'nin yüksek değerleri için bit hızının artışına sebep olur. P_s'nin düşük değerleri için enerji durum değişikliklerinden dolayı sistem performansında artış ve azalışlar meydana gelmiştir. İşbirlikli haberleşme (E_i=2 μJ) için P_s=8 dBm'e kadar, işbirlikli haberleşme (E_i=0,5 μJ) için P_s=10 dBm'e kadar bit hızı 0 kabul edilir. Çünkü, $R_f^2 \geq 1$ bps/Hz şartı sağlanamaz ve optimizasyon probleminin çözümü elde edilemez. Bu sonuç bize düşük P_s değerlerinin uzak kullanıcının iletişimini ciddi manada etkilediğini göstermektedir. Ayrıca durum 1'in aktif olduğu her iki senaryoda P_s'nin artışı, WD_1 kaynaklı girişim sinyalinden dolayı uzak kablosuz cihazın servis kalitesini sağlama koşulunu zorlaştırmaktadır. Bu yüzden α_n güç tahsis katsayısı ile yakın kablosuz cihaza iletilen güç, mümkün olduğu kadar azaltılır.

Şekil 3, terminaller arasındaki uzaklığa bağlı olarak farklı gürültü gücü seviyeleri altında bit hızı değişimini göstermektedir. Buradaki simülasyonda τ=0,05 olarak ayarlanmıştır. Terminaller arasındaki uzaklık artıkça serbest uzay yol kaybı modeline göre kanal kazanç katsayıları düşer ve hasat edilen enerji azalır. Bu sonuç, sistemin bit hızının düşüşüne sebep olur. Grafik incelendiğinde aynı gürültü gücü seviyesinde işbirlikli haberleşme senaryosunun en iyi performans verdiği görülmüştür. Dolayısıyla WD_1'in WD_2 ile simbiyotik bir ilişki içinde olması, sistemin performansı açısından daha verimlidir. Simülasyon parametrelerinde kullanılan gürültü gücünün artışı, FDPS'deki alıcı antenin SNR değerini düşürdüğünden, sistemin toplam bit hızı ciddi manada etkilenmektedir. Şekil 3'ten görüleceği üzere $d_{f\text{-}Ps}$ = 6 m, $d_{n\text{-}Ps}$=4 m değerinden sonra N_0=10^{-10} W için $R_n^1 \geq 3$ bps/Hz $R_f^1, R_f^2 \geq 1$ bps/Hz servis kalitesi gereksinimleri sağlanamadığından optimizasyon probleminin çözümü elde edilemez ve bit hızı 0 kabul edilir. WD_1'in FDPS'a olan uzaklığı artıkça, bit hızı düşer. Ek olarak WD_2 deki WD_1 kaynaklı sinyal girişimi servis kalitesini sekteye uğratır. Bu yüzden yakın kullanıcıya tahsis edilen güç azaltılarak WD_2'nin bit hızının artırılması sağlanır.

Farklı kusurlu ardışık girişim giderici katsayısı altında α_n değişimine göre bit hızı değişimi Şekil 4'te gösterilmiştir. WD_1 ve WD_2'nin simbiyotik olarak işbirliği içerisinde hareket ettiği senaryoda WD_1'e aktarılan güç artıkça WD_2'ye olan yardım artar ve bit hızında yükseliş görülür. Nitekim her iki τ değeri için de işbirlikli senaryonun haberleşme performansı, α_n=0,4 değerinden sonra işbirliksiz senaryoya göre daha iyi performans göstermiştir. İşbirliksiz haberleşme (τ=3x10^{-3}) senaryosunda, α_n'nin artışı ile denklem 16'da paydada yer alan ($P_n d_{n\text{-}Ps} \tau$) ifadesinde artış meydana gelir. Zamansal dengeleme için her ne kadar optimal ϕ_1 değeri uygun olarak ayarlansa da R_f^1 için servis kalitesini sağlamak, sistem performansında düşüşe sebep olur. Ek olarak işbirliksiz haberleşme (τ=3x10^{-3}) senaryosunda α_n=0,9 ve 1 değerleri için uzak kablosuz cihazın servis kalitesi karşılanamadığından problemin çözümü bulunamaz. Bu sonuç, sistem modelinde ele alınan işbirlikli senaryonun diğer senaryoya göre τ parametresinden daha az etkilendiğini gösterir. İşbirliksiz haberleşmede α_n'nin belli bir değerinden sonra bit hızında azalmaların görülmesi, güç tahsis katsayısının uygun bir şekilde ayarlanmasının önemini göstermekte ve önerilen sistem modelinin üstünlüğünü açıkça ortaya koymaktadır.



Şekil 2. FDPS sinyal gücüne göre bit hızı değişimi.

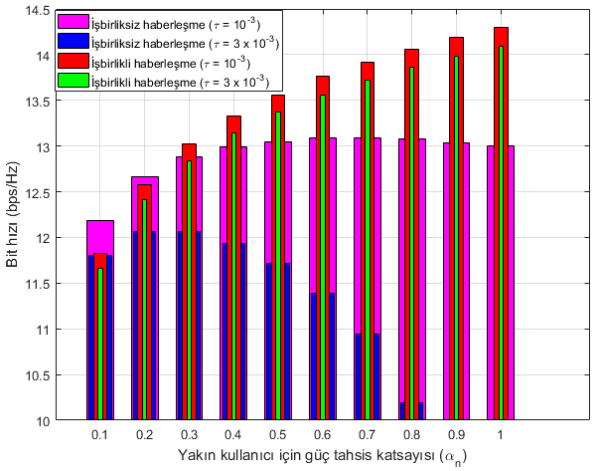


Şekil 3. Terminaller arasındaki uzaklığa göre bit hızı.

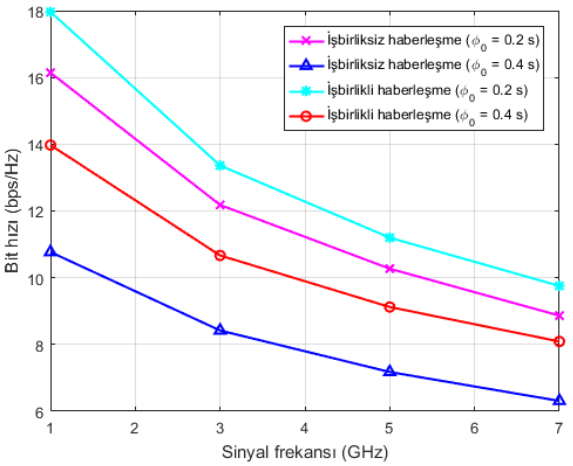
Şekil 5, sinyal frekansının sistemin performansına etkisini farklı ϕ_0 değerleri altında göstermektedir. Elde edilen simülasyon sonucunda, τ=10^{-3} olarak ayarlanmıştır. Sinyal frekansının azalması tüm senaryolar için bit hızının azalmasına sebep olur. Bu sonuç beklenen bir durumdur. Çünkü kanal kazanç katsayıları sinyal frekansıyla ters orantılıdır. Kanal kazanç katsayısı azaldığı takdirde cihazlara aktarılan enerji azalır. Ek olarak cihazlardan FDPS'ye iletilen sinyal gücünde de zayıflama görülür. Sonuç olarak, sistemi çok yüksek frekanslarda kullanmak performansta düşüşe sebep olur. Ayrıca ϕ_0 enerji hasat etme süresini uzun tutmak, cihazların bit iletimi yapma sürelerini kısalttığından aynı senaryo içinde ϕ_0 = 0,2 durumu, ϕ_0 = 0,4 durumuna göre daha avantajlıdır.

4. Sonuç

Bu makalede, elektromanyetik dalgalardan enerji hasat etme tekniğine dayalı iki cihaza sahip çift yönlü simbiyotik radyo ağı için kaynak tahsisi yapılmış ve sistemin toplam bit hızı maksimize edilmiştir. Sunulan sistem, IoT tabanlı simbiyotik ağlarda güç istasyonu çift yönlü düşünülerek hasat edilen enerji seviyesine göre bit hızının maksimize edildiği ilk yaklaşımdır. FDPS terminali, kendisinden yakın ve uzak olarak konumlandırılmış iki farklı cihaza kablosuz olarak enerji aktarımı yaptıktan sonra, bu cihazlar işbirlikli ve işbirliksiz senaryolarda FDPS alıcı antenine bilgi aktarımı gerçekleştirmektedir. Her iki senaryo için enerji hasat etme protokolü ve kanal kapasitesi yazılarak cihazlardaki enerji seviyesine göre toplam bit hızı ifadeleri çıkarılmıştır. Son olarak, nümerik analizle bit hızı maksimize edilip sistem performansı test edilmiştir. Elde edilen sonuçlarda düşük P_S değerinin uzak kullanıcının iletişimini ciddi manada etkilediği görülmektedir. Ayrıca sistemi çok yüksek frekanslarda kullanmanın performansta düşüşe sebep olduğu test edilmiştir. Karşılaştırmalı olarak verilen grafiksel sonuçlarda işbirlikli senaryonun işbirliksiz senaryoya göre sistem parametrelerinden daha az etkilendiği ve performans açısından daha üstün olduğu gösterilmiştir. Gelecek çalışmada, sistem modeline ikiden fazla cihaz yerleştirilerek daha karmaşık ağ yapılarında kaynak tahsis şemaları tasarlanacak ve analizler yapılacaktır.



Şekil 4. Güç tahsis katsayısına göre bit hızı.



Şekil 5. Sinyal frekansına göre bit hızı.

Katkı Oranı Beyanı

Yazarın katkı yüzdeleri aşağıda verilmiştir. Yazar, makalenin son halini incelemiş ve onaylamıştır.

	M.Y.O.
K	100
T	100
Y	100
VTI	100
VAY	100
KT	100
YZ	100
KI	100
GR	100
SY	100

K= kavram, T= tasarım, Y= yönetim, VTI= veri toplama ve/veya işleme, VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= yazım, KI= kritik inceleme, GR= gönderim ve revizyon, SY= sistem yönetimi.

Çatışma Beyanı

Yazar bu çalışmada hiçbir çıkar ilişkisi olmadığını beyan etmektedir.

Etik Onay Beyanı

Bu araştırmada hayvanlar ve insanlar üzerinde herhangi bir çalışma yapılmadığı için etik kurul onayı alınmamıştır.

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BİBER (*Capsicum Annuum* L.) ÇEŞİT ISLAHINDA ETİL METAN SÜLFONAT MUTAGEN ÇALIŞMALARI

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Özet: Dünyada var olan bitkisel kaynakların giderek azalması, insan nüfusunun artması sonucu beslenme ve gıda ihtiyacının karşılanabilmesi için araştırıcılar üretimi artırıcı yollar ve yöntemler üzerine çalışmalar yapmaktadır. Mevcut çeşitlerde bazı kültürel uygulamalardan; sulama sistem ve metotlarının geliştirilmesi, çapalama, gübreleme, hastalık ve zararlılarla mücadelenin iyileştirilmesi gibi çalışmalarla verim ve kalitede sınırlı artış elde edilmiştir. Bitkilerde verim ve kalitede genetik materyal olan tohuma bağlı ıslah çalışmalarının uygulanması ile üstün nitelikli çeşitlerin geliştirilmesi ile mümkün görünmektedir. Bitki ıslahçıları yeni çeşitlerin ortaya çıkarılmasında, doğada var olan varyasyonlardan ve geliştirdikleri yeni teknik ve yöntemlerden faydalanmaktadırlar. Yeni bir çeşidin ortaya çıkarılmasında ıslahçı klasik ıslah yöntemlerinin başında gelen melezleme ıslahından yararlanabildiği gibi, uzun zaman ve fazla emeği kısaltıcı yeni çeşit elde etmede kullanılan yeni bir yöntem olan mutasyon ıslah yöntemini kullanmaya başlamışlardır. Mutasyon, doğada kendiliğinden gerçekleşebildiği gibi, kimyasal ve fiziksel mutajenler kullanılarak da yapılabilmektedir. Doğada yapay olarak elde edilen mutasyonlar çeşitli ışınlar (Gama ışını, X ışını, Kobalt 60 vd.) gibi çok sayıda fiziksel ya da dietil sülfat, sodyum azide ve etil metal sülfonat (EMS) gibi kimyasalların etkisiyle meydana gelirler. Yeni çeşitlerin geliştirilmesinde sıkça başvurulan mutasyon ıslahında kimyasal mutajenler arasında EMS en etkili ve en yaygın olarak kullanılan mutajen olarak kabul edilmektedir. Bu çalışma ile biber çeşit ıslahında EMS uygulamalarına yönelik yapılan çalışmaların irdelenmesi amaçlanmıştır. Böylece biberde EMS ile mutasyon ıslahına yönelik güncel araştırma sonuçları derlenerek; uygulamaya yönelik protokol oluşturulmaya çalışılmıştır. Geniş çeşit potansiyeline sahip biberde her varyasyona yönelik olarak kullanılan uygulama doz ve süreleri gibi faktörlerin dikkate alınarak gelecekte yapılacak çalışmalara referans olabileceği düşünülmektedir.

Anahtar kelimeler: Biber ıslahı, Çeşit geliştirme, EMS, Mutagen

Ethyl Methane Sulfonate Mutagen Studies ın Pepper (*Capsıcum annuum* L.) Breeding Variety

Abstract: Researchers are working on methods to increase production in order to meet the nutritional and food needs as a result of the gradual decrease of the plant resources in the world and the increase in the human population. Some cultural practices in existing varieties; A limited increase in yield and quality has been achieved through practices such as improving irrigation systems and methods, soil mechanization, fertilizing, and control of diseases and pests. The development of high quality varieties possible with the implementation of seed-based breeding studies, which are the genetic material of yield and quality in plants. Plant breeders benefit from the variations existing in nature and using new techniques and methods to develop new varieties. In the emergence of a new variety, the breeder can benefit from hybrid breeding, which is one of the classical breeding methods, and started to use the mutation breeding method, which is a new method used to obtain a new variety that shortens the long time and excessive labor in breeding period. Mutation can occur spontaneously in nature or it can be done by using chemical and physical mutagens. Mutations obtained artificially in nature occur with the effect of many physical such as various rays (Gamma ray, X-ray, Cobalt 60 etc.) or chemicals such as diethyl sulfate, sodium azide and ethyl metal sulfonate (EMS). EMS is accepted as the most effective and common among chemical mutagens in mutation breeding, which is frequently used in the development of new varieties. With this study, it is aimed to examine the studies on EMS applications in pepper cultivar breeding. Thus, by compiling the current research results on mutation breeding with EMS in pepper; an attempt was made to obtain a protocol for implementation. Considering factors such as application doses and time used for each variation of pepper with a wide variety potential, it is thought to be reference for future studies. The observations and experiences of our study that still continued in Dicle University of Agriculture Faculty about EMS applying on pepper will be shared.

Keywords: EMS, Mutation, Pepper breeding, Variety development

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1. Giriş

Dünyada var olan kaynakların giderek azalması ve artan insan nüfusunu besleyebilmek için araştırıcılar üretimi artırıcı yollar ve yöntemler üzerine çalışmalar yapmaktadır. BM'nin öngörüsüne göre 2050 yılına kadar, dünya nüfusunun 9,8 milyara ulaşacağı beklenilmektedir (Kökpınar ve ark., 2021). Artan nüfusu besleyebilmek için birim alandan mevcut üretimin iki katı ürün alınması gerektiği belirtilmektedir (Spencer-Lopes ve ark., 2018). Birim alandan daha fazla ürün alınabilmesi için iki ana

faktör bulunmaktadır. Bunlardan ilki var olan çeşitlerde bazı kültürel uygulamalar üzerine çalışmaların yapılması olarak ifade edilmektedir. Bu uygulamalar; sulama sistem ve metotlarının geliştirilmesi, çapalama, gübreleme, hastalık ve zararlılarla mücadelenin iyileştirilmesi gibi yöntemler üzerinde yoğunlaşmaktadır. Bir diğer yöntem de yeni çeşitlerin elde edilmesi üzerine çalışmaların yapılması şeklindedir. Bitki ıslahçıları yeni çeşitlerin ortaya çıkarılmasında, doğada var olan varyasyonlardan ve geliştirdikleri yeni teknik ve yöntemlerden faydalanmaktadırlar. Yeni bir çeşidin ortaya çıkarılmasında ıslahçı klasik ıslah yöntemlerinin başında gelen melezleme ıslahından yararlanabildiği gibi, uzun zaman ve fazla emeği kısaltıcı yeni çeşit elde etmede kullanılan yeni bir yöntem olan mutasyon ıslah yöntemini kullanmaya başlamışlardır (Kökpınar ve ark., 2021). Mutasyon ıslah tekniği doğrudan olarak veya melezleme ıslahı tekniklerinin tamamlayıcısı olarak da ön plana çıkmıştır (Akbay, 1988).

Mutasyon kelime anlamı olarak organizmanın genom dizisinde meydana gelen kalıcı değişkenlik olarak belirtilmektedir (Ripley, 2013). Bitkilerde mutasyon, bitkinin genetik yapısını değiştiren bir yapı olup doğada kendiliğinden gerçekleşebildiği gibi, kimyasal ve fiziksel mutajenler kullanılarak da yapılabilmektedir (Krupa-Małkiewicz ve ark., 2017). Doğada yapay olarak elde edilen mutasyonlar çeşitli ışınlar (Gama ışını, X ışını, Kobalt 60 vd.) gibi çok sayıda fiziksel ya da dietil sülfat, sodyum azide ve etil metal sülfonat gibi kimyasalların etkisiyle meydana gelirler (Sağel ve ark., 1994). Özellikle yapay olarak yapılan bitki mutasyonlarında (iyonize radyasyonlar, iyonize olmayan radyasyonlar ve kimyasal mutagenler) bitki ıslahçılarının sık sık başvurduğu bir yöntemdir (Çancı ve ark., 2015). Bitki ıslahında mutasyon ıslahı olarak adlandırılan bu yöntemde ana hedef verim ve kalitede artış sağlamak, hastalık ve zararlılarda dayanıklılık sağlamak, pazar değeri yüksek genetik çeşitliliği elde etmek amaçlanmaktadır (Khursheed ark., 2015; Tantray ve ark., 2017; Kazaz ve Kholmurotov, 2022). Araştırmalar kimyasal mutagenlerin kalitesinin, fiziksel mutagenlere göre daha yüksek ve daha ekonomik olduğunu ortaya koymuştur (Devi ve Selvakumar, 2013). Araştırıcılar mutasyona, klasik bitki ıslahına alternatif yöntem olarak bakmaktadırlar. Böyle bakılmasının nedeni mutajenlerin kullanımı ile birlikte, üzerinde çalışılmış birçok bitkide kalitatif ve kantitatif özellikleri ıslah etmede kullanılan hızlı ve etkin bir metot olmasının görülmesinden kaynaklanmaktadır (Gerami ve ark., 2017). Mutasyon ıslahını gerçekleştirmek için hangi mutagenin kullanımının seçimi, çalışılacak türlerde daha önce yapılan akademik çalışmalar ile mutagenlerin mevcudiyeti, maliyetler ve altyapı gibi diğer hususlar dikkate alınmalıdır (Bado ve ark., 2015). Mutayon ıslahında kullanılan tohum veya bitki parçacıkları bir yöreye adapte olmuş genotiplerden mutasyonlar yoluyla hem doğrudan kullanma ve hem de melezlemelerde ebeveyn olarak değerlendirmek üzere yeni gen kaynaklarının bulunmasında pratik bir uygulamadır.

Mutasyon ıslahının gerçekleşme aşamalarında ilk olarak, üzerinde çalışılması gerektiği belirlenen türe fiziksel veya kimyasal mutajenin uygulanması ile başlamaktadır. Daha sonra yapılacak morfolojik ve fizyolojik ölçüm gözlemler sonucu üzerinde çalışılabilecek genotipler seçilir. En sonunda da seçilen bu genotiplerin verim ve kalitesi yüksek olanların karşılaştırmalı testleri yapılarak yeni çeşit elde edilmesi için ıslah süreci başlatılmaktadır (Kökpınar ve ark., 2021). Böylece genetik varyasyonların daralması giderilmekte, adaptasyon yeteneği iyi olan ve tüketimi fazla olan çeşidin bir veya birkaç özelliği iyileştirilebilmekte, bunun yanında yeni özelliklerin ortaya çıkması mümkün olabilmektedir. Çalışma sonunda da yeni çeşitlerin geliştirilmesine katkı sağlamaktadır. Mutasyonla elde edilen mutantların melezleme ıslahında kullanım alanları şöyle sıralanabilir (Sağel ve ark., 2013);

-Orijinal ebeveyn, varyete, hat ile mutantın geriye melezlenmesi,
-Aynı ebeveynden elde edilen mutantların melezlenmesi
-Değişik ebeveynlerden elde edilen mutantların melezlenmesi,
-Farklı tür, varyete veya hat ile mutantların melezlenmesi,
-Benzer mutantları belirgin olarak taşıyan, iki varyetenin melezlenmesi.

Bitkisel üretimde yeni çeşitlerin ortaya konulabilmesi için spontan varyasyon veya klasik ıslah metotlarıyla oluşturulan varyasyon yeterli olmamaktadır. Kullanılacak mutagenler büyük bir popülasyona uygulanabilme olanağı sayesinde, geniş bir varyasyonun ortaya çıkmasına ve bu varyasyonlardan uygun olanların seçilimi ile ıslah amacına yönelik materyallerin teminini sağlamasına katkı sağlamaktadır. Yeni çeşitlerin geliştirilmesinde sıkça başvurulan mutasyon ıslahında kimyasal mutajenler arasında EMS en etkili ve en yaygın olarak kullanılan mutajen olarak kabul edilmektedir (Minocha ve Arnason, 1962; Van Harten, 1998). Bitkilerde kullanılan EMS genellikle nokta mutasyonlarına sebep olmaktadır (Okagaki ve ark., 1991). Mutagen, çoğunlukla Guanin/Citosin'nin Adenin/Timin'e dönüşümünü gerçekleştirerek, yavru döllerde yüksek oranda varyasyon oluşturmaktadır. Kimyasal mutagenler daha çok tohuma uygulanırken; fiziksel mutagenler bitkinin tohum, polen, stolon, yumru, soğan, tomurcuk gibi generatif ve vegetatif üreme organlarına veya bitkinin tamamına uygulanabilmektedir. Bitkilerde uygulanan mutajen dozu için en uygun olanının seçimi son derece önemlidir. Uygulanan mutagen dozu arttıkça mutasyon frekansının artmasıyla beraber, fizyolojik zarar da artmaktadır. Bu nedenle dünyada ve ülkemizde yapılan mutasyon ıslahı çalışmalarında uygulanacak en uygun fiziksel ve kimyasal mutagen dozunu belirleme çalışmaları halen de yapılmaktadır. Uluslararası Atom Enerjisi Kurumunun 2021 yılı verilerine göre, farklı mutagen uygulamaları ile geliştirilen mutant çeşitlerin sayısı fiziksel mutagen uygulamasında 2652 adet, kimyasal mutagen uygulamasında 677 adet, Kimyasal+fiziksel mutagen

uygulamasında 36 adet çeşit tescil edildiği belirtilmektedir. Ajans raporlarına göre Dünya genelinde 21 farklı sebze türünde toplam 172 adet mutant çeşit tescil edildiği belirtilmektedir. Sebzelerde mutasyon yoluyla elde edilen sebze çeşit sayıları Tablo 1'de verilmiştir. Şekil incelendiğinde en çok tescil fasulyede gerçekleştiği (59 adet), ikinci sırada bezelye (34 adet) ve üçüncü sırada biber (16 adet) geldiği görülmektedir (IAEA, 2021).

Mutasyon ıslah teknikleri ile üretici ve tüketicinin talebini karşılamak amacıyla Türkiye'de de enstitülerde, üniversitelerde ve özel sektör aracılığı ile birçok çalışma yapılmaktadır. Bazı sebze türlerinde yapılan çalışmalar şöyledir; biber (Tepe ve ark., 2003; Kantoğlu ve ark., 2014), sarımsak (Taner ve ark., 2004; Beşirli ve ark., 2006), domates (Masuda ve ark., 2004; Kantoğlu ve ark., 2018; Aziz ve ark., 2021), kavun (Kantoğlu ve ark., 2010a), marul (Sarıçam ve ark., 2017) ve havuç (Büyükdinç ve ark., 2019) çalışmaları yapılmıştır.

Bu çalışmanın amacı, biberde Etil Metan Sülfonat kimyasal mutasyon ıslahına yönelik bilgiler verilmeye çalışılmaktadır.

Tablo 1. Bazı sebze türlerinde elde edilen mutant çeşitlerin sayısı (IAEA, 2021)

Tür Adı	Latince Adı	Çeşit Sayısı	Tür Adı	Latince Adı	Çeşit Sayısı
Fasulye	*Phaseolus vulgaris* L.	59	Japon Nanesi	*Mentha arvensis* L.	4
Bezelye	*Pisum sativum* L.	34	Hıyar	*Cucumis sativus* L.	3
Biber	*Capsicum annuum* L.	16	Karpuz	*Citrullus lanatus* (Thunb.) Matsum.& Nakai	3
Kayın Mantarı	*Pleurotus* spp.	8	Bamya	*Abelmoschus esculentus* L. Moench	2
Marul	*Lactuca sativa* L.	7	Mor lahana	*Brassica oleracea* L. var. acephala	1
Patates	*Solanum tuberosum* L.	7	Çin sarımsağı	*Allium macrostemon* L.	1
Soğan	*Allium cepa* L.	6	Ispanak	*Spinacia oleracea* L.	1
Tatlı Patates	*Ipomoea batatas* L. Poir.	6	Japon maydanozu	*Chryptotaenia japonica*	1
Patlıcan	*Solanum melongena* L.	5	Tere	*Lepidium sativum* L.	1
Çin lahanası	*Brassica pekinensis* Rupr.	4	Turp	*Raphanus sativus*	1

1.1. Sebzelerde Mutasyon Islahının Önemi; Etil Metan Sülfonatın Biberde Kullanımı

Sebzelerde mutasyon ıslahı çalışmalarını gerçekleştirmede genetik çeşitliliği elde etmek için kullanılan birçok fiziksel ve kimyasal mutagen bulunmaktadır. Etil metan sulfanat kimyasal mutagenler arasında sebzelerde mutasyon ıslahında çokça başvurulan bir kimyasaldır (Devi ve Selvakumar, 2013). Bu mutagen çoğunlukla gen mutasyonlarına neden olmakta; bu çözelti ile muamele edilen tohumlar daha sonra çimlendirilir ve M1 bitkileri elde edilir. Genellikle toplu seleksiyon şeklinde seçilim yapılan M1 aşamasında tohumlar toplu olarak sezon sonunda toplanır. Bir sonraki yılda ise M2 döllerinde gen mutasyonları gözlenir (Kodym ve Afza, 2003). M2 safhasında teksel seleksiyon yöntemlerinin uygulanması ile istenilen karakterlere sahip hatlar seçilir; bu hatlardan tohumlar alınır. EMS ile fiziksel mutagen uygulamaları kıyaslandığında; EMS'nin küçük kromozom segmentlerinde değişmelere neden olduğu gözlemlenirken, fiziksel mutagenlerin uygulanması sonrasında kromozomlarda delesyon ve duplikasyon gibi yapılarda değişiklikler meydana getirdiği gözlemlenmektedir (Shu ve ark., 2012). EMS Purin ve Pirimidin koklerindeki fosfat gruplarını alkali ederek DNA ile reaksiyona girdikleri belirtilmektedir (Sağel ve ark., 1994).

Kimyasallarla mutasyon oluşturma yöntemlerinden biri olan EMS kullanımı ile bitkinin eşey organlarına (tohum ve çiçek tomurcuğu), eşey hücrelerine (polen, zigot, primitif embriyo ve yumurta), klonlarına (yumru, rizom, stolon, kök, köklenmiş çelikler), fidelerine, odun gözlerine ve vejetatif organlara (sap, kardeş, yaprak, çiçek yaprakları) gibi yapılardan herhangi biri seçilebilmektedir (Arisha ve ark., 2015; Bado ve ark., 2015; Güvercin, 2020). Ancak yapılan akademik çalışmalar incelendiğinde en çok başvurulan yöntem, EMS'ye ait mutagen solüsyonlarının bitkinin tohumlarını ıslatması şeklinde yapıldığı görülmektedir (Salam ve Thoppil, 2010; Jeong ve ark., 2012; Sanjai Gandhi ve ark., 2014). Öncelikle bitki çeşidine göre uygun kimyasal konsantrasyonu hazırlanır ve tohumlar bu solüsyon içinde ıslatılır. Islatma süresi bitki çeşidine göre değişebilmektedir.

Mutasyon ıslahında sebzelerin genelinde uygulanan EMS, biber sebzesinde de benzer yöntem ve kurallar ile uygulanmaktadır. Yapılan akademik çalışmalara ek olarak Dicle Üniversitesi Ziraat Fakültesi Bahçe Bitkileri Bölümünde doktora tezi için iki yıl üst üste kurulan ön denemelerde elde edilen sonuçlar değerlendirilerek, biber sebzesinde etkili EMS dozları önerilmeye çalışılmıştır. Elde edilen bulgulara göre EMS'nin %0,1; 0,2; 0,3; 0,4 ve 0,5 dozlarında biberde etki yaptıkları belirlenmiştir. Yapılan ön çalışma sonucunda, %0,75 ve %1,0 dozlarının biber tohumlarının çimlenme sürelerini uzattığı ve bazı tohumlarda çimlenme yeteneklerin kaybettikleri tespit edilmiştir. Düşük dozlarda yapılan uygulama çalışmalarına göre (%0,1 ve %0,2), mutasyonun etkinliğinin daha az olduğu bulunmuş;

dozların artması ile beraberinde (%0,3; %0,4 ve %0,5 dozları) elde edilen çeşitliliğin arttığı çalışmamızda tespit edilmiştir. Sonuç olarak EMS mutageninin biberde yaptığı etkiler bakımından incelemeler yapıldığında; dozların artması ile beraber genel olarak biber tohumlarının çimlenme sürelerini uzattığı veya tohumların canlılığını kaybettirdiği, bitkinin kısa boylu kalmasına neden olduğu, çiçeklenmeyi geciktirdiği, meyvelerde şekil değişikliklerine yol açtığı tespit edilmiştir (Devi ve Selvakumar, 2013; Kantoğlu ve ark., 2014; Pharmawati ve ark., 2018). Bu nedenle yapılacak çalışmalarda etkili dozun kullanılmasına dikkat edilmelidir. Biberde EMS'nin dozlarının belirlenmesine yönelik yapılacak çalışmalarda, uygulama süresinde ve uygulanması sırasında dikkat edilmesi gereken faktörler şöyle sıralanabilir;

-Tohumların ön ıslatılması; biber tohumlarına yapılacak ön ıslatma ile beraber bu tohumların kimyasal mutagenlerle duyarlılıklarının artırıldığı yapılan akademik çalışmalarda ve üniversitemizde yapılan çalışmalarda tespit edilmiştir. Tohumların 20°C'de 6-12 saat ön ıslatmaya tabi tutulduğunda mutagenin tohumlarda daha fazla nüfuz ettiği belirtilmektedir (Arisha ve ark., 2014; Arisha ve ark., 2015; Cheng ve ark., 2019).

-Uygulanacak EMS'nin dozu; kullanılacak sebze tohumlarının çeşidine bağlı olarak önem arz etmektedir. Sebzelerin istedikleri konsantrasyonlar farklı olabilmektedir. Uygulanacak doz bitki çeşidi başta olmak üzere uygulama süresine ve uygulama yapılan çevre sıcaklığına göre de hazırlanmaktadır. Bu nedenle uygulamadan önce yapılan önceki çalışmalar dikkate alınmalıdır. Kullanılacak EMS dozlarının artmasıyla beraberinde bitkilerin fizyolojisinde hasarlar meydana getirebilmektedir. Bu nedenle kullanılacak mutagen dozu bitkide düşük oranlarda fizyolojik zararlar ile yüksek genetik çeşitliliğe yol açmasını istenmektedir (Gaul, 1963; Altıntaş, 2020). Araştırıcılar etkili olabilecek dozu belirleyebilmek için LD 50 değerinin (%50 öldürücü doz) bitkilerde öncelikle belirlenmesini önermektedirler (Walter ve ark., 1987; Sağel ve ark., 2003). Bu etkili dozu belirleyebilmek amacıyla da sebzelerde ön çimlendirme çalışmaları gibi çalışmalar yaparak artan dozlarda EMS uygulaması yapıp, öldürücü dozu tespit etmektedirler. Sebzelerin tür ve çeşidine göre etkili doz farklılık göstermektedir. Biberde yapılan mutasyon ıslah çalışmaları dikkate alındığında (Lambat ve ark., 2012; Devi ve Selvakumar, 2013; Soyam, 2021) EMS'nin %0,2; %0,3 ve %0,4 dozlarının etkili olduğu rapor edilmiş; bu sonuçları destekleyen araştırma üniversitemizde de yapılan iki yıllık ön çalışmalar sonucunda da tespit edilmiştir. Yapılan incelemeler sonucunda, dozların artması ile beraber bitkide fizyolojik ve morfolojik bozulmaların yaşanmaya başladığı rapor edilmiştir. Biber tohumlarının maruz bırakıldığı solüsyon belirli aralıklarla çalkalanmasıyla tüm tohumlara nüfuz edeceği de bilinmelidir.

-EMS'nin uygulama süresi; mutagenin dokuya en iyi şekilde nüfuz edebilmesi için uygulama süresi uzun tutulmalıdır. Bu süre kullanılacak bitki çeşidine ve bitki organlarına göre değişebilmektedir. Ancak dikkat edilmesi gereken nokta; EMS'nin uygulama süresi uzadıkça çimlenme ile ilgili karakterlerde genel bir azalmaya neden olduğunu araştırıcılar rapor etmektedir (Pour ve ark., 2021). Yapılan akademik çalışmalar değerlendirildiğinde ortalama 6 ile 12 saat arasında değiştiği görülmüştür (Arisha ve ark., 2014; Arisha ve ark., 2015; Tantray ve ark., 2017). Uygulama süresini etkileyen diğer bir unsur; bitki materyalinin ön ıslatılması ile uygulama süresi kısalmaktadır (Pakyürek, 2020).

-EMS uygulanacak ortamın sıcaklığı; EMS mutageninin hidroliz oranında ortam sıcaklığı önemli rol oynamaktadır. Kısa hidroliz süresine sahip mutagenlerde ortam sıcaklığının yüksek olması ile uygulama süresi kısa olabilirken; sıcaklığın düşmesi ile beraber uygulama süresi artabilmektedir (Jenks ve ark., 2007; Pour ve ark., 2021). Biber tohumlarına ortalama oda sıcaklığında muamelelerin yapılması (20-25 ^{o}C) önerilmektedir (Alcantara ve ark., 1996; Cheng ve ark., 2019).

- EMS uygulaması sonrasında tohumların yıkanması; mutagen uygulaması sonrasında bu tohumlara herhangi bir işlem yapılmadan kurutulduğunda mutagenin etkisi devam etmektedir. Hiçbir işlem yapılmadan ekilen tohumlarda %100 ölüm meydana geldiği bildirilmektedir. Bu amaçla kısa bir yıkama periyodunun yeterli olduğu bildirilmektedir. Mutagenin tohum üzerindeki etkisini azaltmak için çeşme suyu altında 1-3 saat arasında yıkanması önerilmektedir (Arisha ve ark., 2015; Tantray ve ark., 2017; Cheng ve ark., 2019). Daha sonra bu tohumlar kurutma kâğıdında kurutularak ekim yapılmaktadır.

Bu işlemlerin yapılmasından sonra ekimleri yapılan tohumlardan elde edilen generasyonlara M1 ismi verilmektedir. Bu işlemin ikinci defa yapılmasıyla elde edilen tohumlara da M2 generasyonu denmektedir. Mutasyon ıslahında dikkat edilmesi gereken konu; üreticinin istediği özelliklere sahip mutantların seçiminin hangi generasyonda başlayacağıdır. Birinci generasyonda değerlendirme yapmak uygun değildir, çünkü elde edilen bitkiler genotipik olarak heterojen (kimerik), fiziksel anlamda mutagen etkisi nedeni ile hala kendini tam olarak gösterememektedir. Tohumla çoğaltılan materyallerde ilk kimerik olmayan (homohistont) generasyon M2'dir. Vejetatif olarak çoğaltılan bir materyali genotipik olarak homojen hale getirmek ve mutant alellerin kalıtımını kalıcı hali getirmek için birkaç generasyona ihtiyaç vardır. Sonraki generasyonlar genellikle mutant fenotiplerin değerlendirilmesi için seçim aşamalarını içermektedir. Bu işlem tamamlandıktan sonra, materyaller çeşitli arazi denemelerine alınmaktadırlar. Yapılan mutasyon yoğunluğu da dikkate alınarak M2 aşamasında stabil fenotiplerin seçimi bazen zor olabilmektedir. Fenotipik olarak seçilen hatların gözlemlenen özellikleri sonraki generasyonlarda kaybolabilmektedir. Araştırıcılar bunun nedenini, bağlı olmayan allellerin döller boyunca

bağımsız olarak ayrılmalarından kaynaklı olduğunu belirtmektedir (Kantoğlu ve ark., 2014; Kökpınar ve ark., 2021). Birçok araştırıcı daha fazla karakterizasyon elde edebilmek için bunu bilerek hatları seçmeye devam eder, M2 generasyonunda fenotipik bakımdan ilgi çekici olan her şeyi seçebilmektedir. Ancak en sağlam metot benzersiz mutasyonların keşfini en üst düzeye çıkarmak için moleküler markırların kullanılması önerilebilir (Kantoğlu ve ark., 2014). EMS'nin sebzelerde mutasyon ıslahında kullanılmasıyla beraber; verimde, çiçeklenme tarihleri ve olgunlaşma zamanlarında, bitkinin yatmaya veya gövde kırılmalarında mukavemette, biyotik ve abiyotik stres faktörlerine hassas veya dayanıklı türlerin gelişiminde, hastalık veya zararlılara mukavemette, kalitede değişimlere yol açabilmektedir. Islahçı bu süreçten sonra istediği parametrelere göre seçilim yaparak bu türlerin ıslahını gerçekleştirmektedir (Rao ve ark., 1997; Kantoğlu ve ark., 2010b; Dongfu ve ark., 2022).

Daha sonraki generasyonlarda yapılacak iş/işlemler şöyle olmaktadır (Jankowicz-Cieslak ve Till, 2015; Kökpınar ve ark., 2021);

a. M3 -M8 generasyonlarında; seleksiyon işlemleri, genetik doğrulama, kalite analizleri, mutant hatların arazi performans takipleri
b. Sonraki 2-3 generasyon; farklı yıllarda lokasyonlarda mutant hatların ekimlerinin yapılmasıyla karşılaştırılmaları
c. Sonraki 2-3 generasyon; yeni bir çeşit/çeşitlerin ortaya çıkarılması.

Dongfu ve ark. (2022), biberde (*Capsicum annuum*) genetik varyasyonlarını artırmak amacıyla yaptıkları çalışmalarında, ölümcül doz %50 (LD50) değerini belirleyebilmek için, farklı mutajenez sürelerinde farklı EMS konsantrasyonlarında biber tohumlarını göreceli çimlenme oranlarını analiz etmişlerdir. Ayrıca M1ve M2 neslinin farklı gelişim aşamalarında, yaprak şekli, çiçek organı, gövde, yaprak rengi, doğurganlık ve meyve şeklinde mutasyonlar gözlenmiş ve yaprak rengi ve doğurganlık kimeralarını da tanımlanmışlardır. Çalışma sonunda elde edilen bulgulara göre uygulanan dozların sadece genetik modifikasyon uygulamaları için değerli olmadıkları; aynı zamanda biberlerin yeni genlerinin keşfi için de büyük etkilere sahip olduğu rapor etmişlerdir.

Soyam (2021), EMS'nin farklı dozlarının (%0,2, %0,3 ve %0,4) M1 neslinde biberin klorofil içeriği ve askorbik asidi üzerindeki etkisini araştırdığı çalışmasında, askorbik asit içeriğinin, kontrole kıyasla EMS dozu/konsantrasyonunda bir artışla azaldığını belirtmiştir. Klorofil içeriğinde ise, maksimum klorofil 'a've toplam klorofil içeriğinin EMS uygulamasının daha yüksek dozunda, klorofil 'b' içeriğinin ise EMS'nin düşük dozunda belirlediğini rapor etmiştir.

Tanaka ve ark. (2021) acı biberde çekirdeksizliği elde etmek için bağlı olan mutantın karakterizasyonunu belirlemeye yönelik yaptıkları çalışmalarında tn-1 olarak adlandırdıkları mutantı, etil metan sülfonat ile mutajenize edilmiş popülasyonun taranmasıyla bulduklarını rapor etmişlerdir. Yabani tip meyveler yaklaşık 40 tohum içerirken, tn-1 hiç tohum içermemiş ya da çok az tohum içeren meyveler olarak belirledikleri çalışmada, çekirdeksizliğin tek bir resesif gen tarafından belirlendiği belirtilmiştir. Siddique ve ark. (2020) biberde etil metan sülfonat tarafından uyartılmış mutant popülasyonlarının gelişimi ve karakterizasyonunu belirlemeye yönelik yaptıkları çalışmalarında, 9500 tohumu %1,3 EMS ile muamele ederek 3996 M2 hattı hasat ettiklerini belirtmişlerdir. Sonraki yıl 1300 (%32,5) bağımsız M2 ailesi seçilmiş ve dört yıl boyunca fenotiplerini değerlendirmişlerdir. Mutantlar bitki büyümesinde, adaptasyonunda, yaprak rengi, şekli ve çiçekte fenotipik varyasyonlar oluşturduğu rapor edilmiştir.

Juliandari ve ark. (2019) etil metan sülfonat (EMS) (%0, %0,01, %0,02 ve %0,04) ile uyartılmış yerel acı biberde genetik varyasyon analizi için Mikrosatellit Markörünü kullandıkları çalışmalarında kontrol bitkisi ile karşılaştırıldığında yerel acı biberde genom düzeyinde genetik varyasyonlar gözlemlendiğini rapor etmişlerdir. Ayrıca, %0,04 konsantrasyonlu EMS uygulaması, yerel biberin 3 genotipinde en kayda değer genetik varyasyonu ürettiği belirtilmiştir. Cheng ve ark. (2019) çalışmalarında, biberde yaprak rengi mutantlarinin fizyo-biyokimyasal karakterizasyonunu belirlemek için etil metan sülfonat uygulaması yapmışlardır. Araştırmada etil metan sülfonat mutajenize edilmiş biber bitkisinde tanımlanan zylm soluk yeşil yaprak mutantı yabani biber popülasyonunda yaprak renginin biber üzerindeki etkisini incelenmiş; çalışmada doğal tarla koşullarında, zylm mutant bitkilerinin yaprakları bozulduğu, büyüme ve solgunluk sergilediği belirtilmiştir.

Pharmawati ve ark. (2018) biberde etil metan sülfonat (%0,5, %0,75 ve %1 EMS) ile muamele edilmiş tohumlardan elde edilen M2 bitkilerindeki morfolojik varyasyonu belirlemeye yönelik yaptıkları çalışmalarında, EMS uygulamaları nedeniyle hem fide çıkışında hem de bitki sağ kalımında bir azalma olduğunu belirtmişlerdir. Araştırıcılar M2 neslinde, %1 EMS uygulanmış bitkilerin uzun boylu, soluk yeşil yaprak rengine sahip küçük bitkileri, bodur bitki ve iki gövdeli bitki ürettiğini rapor etmişlerdir. %0,75 EMS uygulanmış bitkilerin, birçok dalı olan kısa mutantla sonuçlanırken, %0,5 EMS soluk yeşil yaprak rengine sahip bitki ürettiği belirtilmiştir. Araştırıcılar sonuç olarak, EMS mutajenezinin biberde ıslah programlarında kullanılabileceğini ve kontrol bitkilerinden farklı ilginç morfolojik karakterlere sahip yeni bitkilerin ortaya çıktığını belirtmişlerdir.

Shah ve ark. (2016) etil metan sülfonat (EMS) mutajenik etkisini inceledikleri çalışmalarında, EMS'nin yüksek sıklıkta nükleotid ve substitüsyon varyasyonlarına neden olduğu için bitki sistemlerinde sıklıkla ve bol miktarda kullanıldığı belirtilmiştir. EMS'nin çok çeşitli genetik test sistemlerinde arzu edilen karakterlere sahip yeni mutantlar üretmek için biyolojik sistemler üzerinde daha

az etkiye sahip, kolayca bulunabilen bir mutajen olarak bulunduğunu belirtmişlerdir.

Devi ve Selvakumar (2013) Biberde kimyasal mutajenler yoluyla üretilen değişkenliği karşılaştırmak için yaptıkları çalışmalarında, etil metan sülfonat (10, 20, 30, 40 ve 50 Mm) ve dietil sülfat (5, 10, 15, 20 ve 25 Mm) farklı dozlarını uygulamışlardır. Elde edilen sonuçlara göre, en yüksek çimlenme yüzdesinin uygulama yapılmamış tohumlardan (kontrol) %75.3 olduğunu rapor etmişlerdir. Genel olarak, 40 ve 50 mM EMS ve 25 mM DES'in biber türlerinin çiçek gelişimi üzerine olumsuz etkisi olduğu belirtilmiştir. Lambat ve ark. (2012) gama ışınlarının (10 KR, 20 KR ve 30 KR) ve etil metan sülfonatın (%0,1, %0,2 ve %0,3) biber üzerindeki sitolojik ve morfolojik etkisini araştırdıkları çalışmalarında, çeşitli nükleer ve kromozomal anormallikleri indüklediğini rapor etmişlerdir.

Dhamayanthi ve Reddy (2000), acı biberde gama ışınları ve etil metan sülfonatın sitogenetik etkilerini inceledikleri çalışmalarında; 15, 25, 35 kR dozlarda gama ışını ve %0,8 ile %1 etil metan sülfonat (EMS) dozlarını uygulamışladır. M2 safhasında mutajenik uygulamaların etkileri belirlenmiş; mayoz bölünmenin kromozomal anamolileri, polen kısırlığı, tohum kısırlığı ve hayatta kalma yüzdesini araştırıcılar incelemiştir. EMS'nin mayotik düzensizliklerin indüklenmesinde gama ışınları uygulamasına göre daha etkili bulunduğu rapor edilmiştir. Ayrıca tüm uygulamalarda mayotik anomalilerde doza bağlı bir artış olduğu rapor edilmiştir.

2. Sonuç ve Öneriler

Bitkilerin sahip olduğu üstün karakteristik özelliklerinden yararlanmak için ıslahçılar bu tohumlar üzerine çalışmalar yapmaktadır. Birim alandan yüksek oranda verim almanın yolu tohumun verimliliği ile yetiştiricilikte yapılacak kültürel işlemlerin etkinliği ile mümkün olabilmektedir. Ancak tohumun verimsiz olması halinde yapılacak en üst kültürel işlemlerde bile verim elde edilememektedir. Bu nedenle ıslahçılar sürekli yeni çeşitlerin geliştirilmesi üzerine çalışmalar yapmaktadır. Çeşit geliştirmede zaman ve etkinlik bakımından etkili olan EMS uygulaması olumlu sonuçlar vermektedir.

Yapılan çalışmaların bir araya getirilmesi ve fakültemizde yapılan ön çalışmalarda elde edilen bulgular sonucunda EMS'nin biberde çeşit geliştirmede etkili olduğu tespit edilmiştir (Tepe ve ark., 2003; Kantoğlu ve ark., 2014; Soyam, 2021; Tantray ve ark., 2017).

Biberde çeşit geliştirmede uygulanacak etkili mutant dozu ile başarı paralel elde edilmektedir. Çalışmalara başlamadan önce ön çimlendirme çalışmalarının yapılması sonucu etkili dozun belirlenmesi mümkün olabilmektedir. Biber çeşitlerine göre EMS'nin dozlarının etkinliği farklı olabileceğinden, kullanılacak çeşit ve kullanılacak dozların belirlenmesi başarıyı da etkilemektedir. Biber başta olmak üzere diğer sebze tür ve çeşitlerinde ilk etapta etkili dozun belirlenmesi önerilmektedir. Biber çeşitlerine göre, çalışmanın yapılacağı ekolojiye göre ve uygulanacak kültürel işlemlere göre mutajen dozlarının etkinliğinin değişebileceği düşünülmektedir. Biberde ıslah amacıyla etil metan sülfonatın kullanımında uygulamaya yönelik protokol şöyle özetlenebilir;

a. Kullanılacak tohumların açılım göstermeyen tek tip genotip veya çeşide ait olmasına özen gösterilmeli (aynı genotip veya çeşide ait farklı karakteristik özelliklerdeki biber tohumlarına uygulanacak EMS, ortaya çıkacak farklı bitkilerin neden kaynaklandığına yönelik bilinmezlik içerir. Bu nedenle saf tohumlar ile çalışma başlatılmalıdır). Yapılan akademik çalışmalar incelendiğinde bitki materyali tohumların tamamı ya çeşit olarak veya da saflaştırılmış genotiplerden oluştuğu bilinmektedir. Omosun ve ark. (2022) iki farklı bamya çeşidine ait tohumlarda EMS uygulamalarının tohum çimlenmesi, büyümesi ve verimini araştırdıkları çalışmalarında artan konsantrasyonlarda EMS varlığı (%0,5) ile tohumların zarar gördüğünü rapor etmişlerdir. Benzer çalışma Baghery ve ark. (2015) tarafından bamya tohumlarında yapılan çalışmada da rapor edilmiştir.

b. Tohumlara EMS uygulamadan önce 6-12 saat aralığında suda bekletilmeleri tohumların mutagen ile daha iyi muamelesine katkı sağlamaktadır.

c. Biber ıslahında yeni çeşitlerin elde edilmesi için uygulanacak EMS dozu çeşitlere bağlı olarak %0,2, %0,3 ve %0,4 dozlarında genel olarak iyi sonuçlar verdiği birçok çalışmada rapor edildiğinden, bu dozların kullanımı da istenilen başarıya götüreceği düşünülmektedir (Ariraman ve ark., 2014; Omosun ve ark., 2022) . M1'deki farklı fiziksel ve kimyasal mutajenlerin bitkilerde oluşabilecek etkilerini tanımlamak için fide boyu çoğunlukla bir endeks olarak kullanılmaktadır (Upadhyaya ve ark., 2007; Talebi ark., 2012). Fide boyu ile fiziksel veya kimyasal mutajenlerin dozu arasında doğrusal bir bağımlılık olduğu belirtilmektedir. Bundan dolayı ıslah çalışmalarında fideliklerde oluşabilecek fide boyundaki kısalmalar EMS konsantrasyonundaki artışlardan kaynaklandığı bilinmelidir. Islahçılar da istenilen boyutlardaki bitki boyları için dozları buna göre seçilim yapması önerilmektedir.

d. EMS' nin uygulama süreleri arttıkça tohumda oluşabilecek tahribatlar da (canlılığını yitirmesi gb.) artabileceğinden uygun sürenin 6 ile 12 saat aralığında olmasına özen gösterilmelidir.

e. Biber bitkisinin çiçekleri büyük oranda erselik çiçek yapısına sahip olduğundan, yabancı tozlaşma ve döllenme oranı da çok yüksek değildir. EMS uygulanmış bitkilerde yabancı tozlaşma ile ortaya çıkabilecek farklılıkların önüne geçilebilmesi için, çiçeklenme başlangıcında pratik olması dolasıyla tüm bitki hava geçiren ince tülbent benzeri yapılarla örtülerek dışarıdan çiçeklere herhangi bir tozlaşma gerçekleşmesine engel olunmalıdır. Çünkü dışarıdan gelecek farklı bir çiçek tozu çeşit elde etmede yanıltıcı sonuçlara götürebilmektedir. Bu durum önüne geçebilmek için de ayrıca izolasyon mesafelerine dikkat

edilmelidir.

f. Uygulama yapacak kişi ve kişilerin bu kimyasalın yüksek zararlı etkisinin bilincinde olarak çalışması gerektiği bilinmelidir. Cilt ile temasın kesilmesi için vücudun herhangi açık yüzeyi bulunmamalı; önlük, eldiven ve gözlük kullanımına dikkat edilmelidir. Uygulama sonucunda geriye kalan kimyasallar lavabolara dökülmemeli; belediyelerin zararlı atık madde hizmetleri ile imha edilmelidir.

Sonuç olarak artan dünya nüfusunu besleyebilmek için gıda üretiminin sürdürülebilirliği ve artırılmasında biber başta olmak üzere diğer sebze türlerinde yapılacak olan mutasyon ıslahında, var olan genetik kaynakların çeşitliliğinin genişletilmesinde EMS önemli bir rol oynamaktadır.

Katkı Oranı Beyanı

Yazarların katkı yüzdeleri aşağıda verilmiştir. Yazarlar makaleyi incelemiş ve onaylamıştır.

	E.A.	V.P.
K	50	50
T	50	50
Y	50	50
VAY	50	50
KT	50	50
YZ	50	50
KI	50	50
GR	50	50

K= kavram, T= tasarım, Y= yönetim, .VAY= veri analizi ve/veya yorumlama, KT= kaynak tarama, YZ= Yazım, KI= kritik inceleme, GR= gönderim ve revizyon.

Çatışma Beyanı

Bu makalenin hazırlığı ve yazımında yazarların çıkar çatışması olmadığını beyan etmektedirler. Ayrıca çalışmanın yapılmasında fon sağlayıcıların çalışmanın tasarımında, verilerin toplanmasında, analiz edilmesinde veya yorumlanmasında; makalenin yazılmasında veya sonuçların yayınlanması kararında herhangi bir rolü yoktur.

Kaynaklar

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