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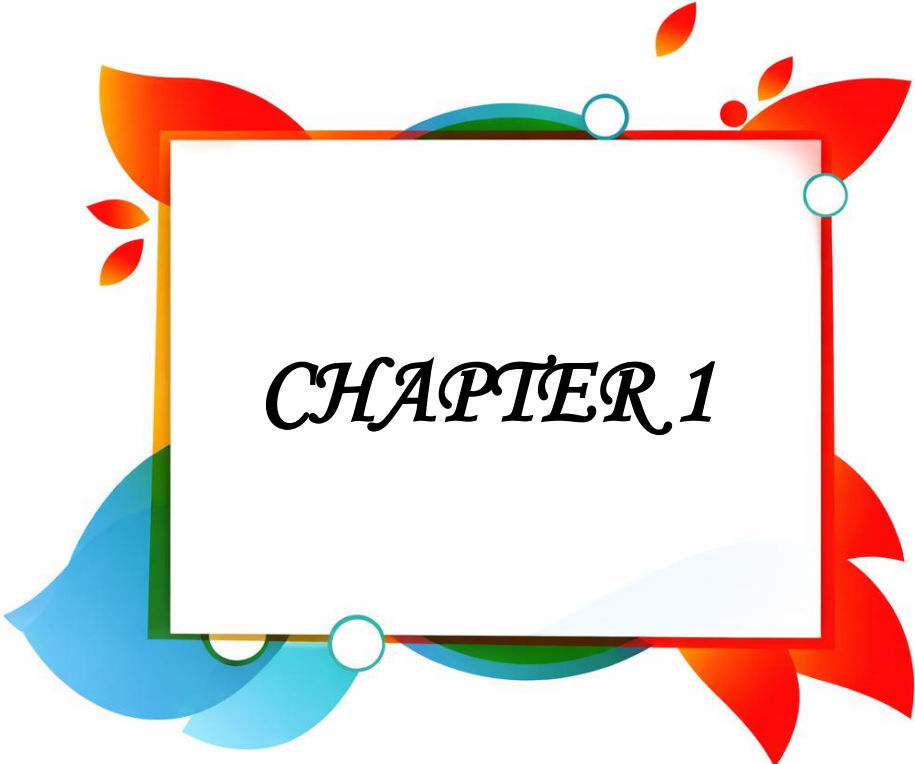
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CHAPTER 1

Integration of Artificial Intelligence into the Experimental Design Process in Forest Industrial Engineering: An Educational Approach

Emine Seda Erdinler¹ & Sedanur Seker²

Introduction

Today, artificial intelligence (AI), with its human-like cognitive abilities such as learning, problem-solving, decision-making, and performing complex tasks, is rapidly developing in many fields. Considered as an interdisciplinary technology, AI is becoming increasingly widespread not only in the business world but also in different areas of education. One of these educational fields is the discipline of forest industry engineering addressed in this study.

Artificial intelligence (AI) currently plays an important role in many areas of our lives. It has a wide range of applications, from facial and voice recognition systems to disease diagnosis and language translation (Russell and Norvig, 2021; Marr, 2020). It is rapidly advancing across many disciplines with its capacity to derive meaningful results from complex datasets, imitate human behavior, and in some cases produce solutions that surpass human intelligence (Goodfellow, Bengio and Courville, 2016; Silver et al., 2016). However, it is also considered that artificial intelligence has limitations in abstract and human-centered fields such as design and creativity. Researchers argue that AI cannot fully imitate the fundamental characteristics of human consciousness, such as social intelligence and empathy, and therefore cannot produce designs as effectively as humans (Dautenhahn, 2007; Boden, 2016; Gunkel, 2012). These limitations become more evident especially in fields such as spatial design, which require creativity and a deep understanding of human experience (Lawson, 2006; Cross, 2006).

With the introduction of technological opportunities, significant developments have occurred in design processes, and technological tools have emerged that enable students to realize what they imagine in a more practical, faster, and lower-cost manner (Kaleja and KavutKozlovska, 2017; Oxman, 2017). Designers can create designs that address users' needs and emotions by

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considering the aesthetic, functional, and emotional dimensions of space. However, it is currently difficult for artificial intelligence to develop such empathy and deep understanding (Eskicioğlu and Öztürk, 2020; Gero, 2010). On the other hand, rapid developments in AI technologies raise the possibility that artificial intelligence may play a more active role in design processes in the future and imitate human creativity, or even reveal new forms of creativity (Akdemir, 2017; Gu and Behbahani, 2021; Ge and Hou, 2025).

Artificial intelligence can provide innovative solutions in collaboration with human designers by developing tools that support design thinking and creativity. This means that artificial intelligence can not only imitate existing design practices but also bring new perspectives and approaches to design processes (Boden, 2016; Rezwana and Maher, 2022). Architecture has historically been a discipline open to change and transformation, and this evolution is also observed in interior architecture. Design is a process carried out by the human mind through imagining and attempting to create what does not exist (Akdemir, 2017; Lawson, 2006). Artificial intelligence technologies provide designers with the opportunity to reveal what they imagine within their own designs (Oxman, 2017; Caetano and Leita, 2020).

The design process begins with defining the objective and continues with analysis, which is the stage of collecting and organizing the necessary information. Subsequently, alternative solutions for the design problem awaiting resolution are developed during the synthesis stage, and these options are evaluated according to predetermined criteria to select the most appropriate solution (Dorst, 2011). The act and concept of design include intelligence in a way that encompasses the formation and functioning of algorithms. In this context, design is a form of thought open to evolution, whereas intelligence and algorithms are mechanisms capable of producing such development-oriented thoughts (Gero, 2010; Kolodner, 1993).

The interior designer is the main actor who initiates the interior space design process and applies an abstract filter to the design by making unique selections. Thus, interior space design is shaped according to the designer's learning process and choices (Eskicioğlu and Öztürk, 2020). Interior architecture education is also transforming through technology and digitalization, evolving from the dynamic interaction of the master-apprentice relationship toward project-based teaching models (Nas and Kavut, 2023; Schön, 1983). While students express their ideas and designs through drawing and presentation techniques, education largely relies on visual expression. With the influence of digitalization, technological tools contributing to two- and three-dimensional design are being used to enable students to realize their imaginations in a more practical, faster, and lower-cost manner (Oxman, 2017; Gökdemir and Kayan, 2025).

Forest industry engineering is a multidisciplinary engineering field aiming at the sustainable and efficient processing, utilization, and integration of forest products into industrial processes (Demir et al., 2020; Özdemir, 2018). This discipline is directly related to sectors such as furniture design and production. The use of artificial intelligence technologies in this field optimizes many processes ranging from production planning to quality control, and from material analysis to energy efficiency (Zhoy et al., 2022; Altun et al., 2019). For example, while productivity is increased through machine learning algorithms in production lines, raw material losses are reduced and production costs are optimized. Through image processing techniques, the physical defects of wooden materials are automatically detected, while predictive models foresee failures in production equipment in advance, enabling maintenance processes to be planned more effectively (Çelik et al., 2023; Kahraman et al., 2024; Lei et al., 2020).

In furniture design, artificial intelligence offers innovative solutions in both aesthetic and functional aspects. Machine learning algorithms analyze user preferences and support the development of personalized and ergonomic furniture designs (Lin, 2025; Lin et al., 2023). In addition, AI-supported big data analyses contribute to the development of strategic and data-driven approaches in the furniture sector by enabling the accurate evaluation of market trends and consumer demands (Süleymanoğlu et al., 2022; Jiang, 2025).

When spatial design and survey studies are also supported by artificial intelligence, the processes of transferring existing structures and interiors into digital environments, analyzing them, and developing new design solutions become easier. Three-dimensional modeling of survey data allows more accurate and faster results in material and structural analyses through AI-based methods (Ozar and Koca, 2024). In this way, both the design process is accelerated and the functionality and aesthetics of spaces are enhanced.

All these developments make it necessary to integrate artificial intelligence into forest industry engineering education through the fields of furniture design, spatial design, and survey studies, thereby enabling the development of innovative, sustainable, and user-oriented design approaches (Gedik et al., 2018; Nas and Kavut, 2023).

Within the scope of the related course constituting the sample of the study, students were first divided into groups according to predetermined criteria, and each group selected a different space for conducting a survey study. The characteristic and physical properties of the selected spaces were examined in detail, and factors such as architectural elements specific to the space, material structure, lighting, and spatial organization were analyzed. In light of these data, students carried out an experimental design process by using their own perceptions and interpretation methods. Throughout the design process, various

digital tools and methods provided by artificial intelligence technologies were used with the aim of supporting and optimizing design decisions.

Materials and Methods

This study was conducted within the scope of the “Interior Space Decoration” course included in the undergraduate program of Forest Industry Engineering. The main purpose of the research is to develop an applied model for the integration of artificial intelligence technologies into design-oriented project courses. In this context, the study process began with students selecting specific interior spaces located within the faculty building where they study. Within this scope, selections were made among spaces with different functions located in the Faculty of Forestry, such as classrooms, corridors, waiting areas, consultation units, or offices (Figure 1).



Figure 1. Some visuals of six different interior spaces selected by the students within the scope of the study.

During the selection process, criteria such as the measurability of the space, its usage condition, and the level of intervention feasibility were taken into consideration.

In the first stage of the study, technical applications such as measurement taking through survey studies of the determined interior spaces, preparation of existing plans and sections, documentation of structural elements, and material and surface analyses were carried out.

In research articles, the materials used, methods applied, and techniques employed should be clearly explained in this section. In terms of the reproducibility of the study, the method should be presented in a detailed and

explicit manner. The methods used should be supported by previously published references. During this process, detailed data were collected by utilizing both manual measuring tools and digital measurement technologies (laser distance meters, mobile applications, etc.). In the following stage, text-based commands (prompts) directed to artificial intelligence systems were consciously created in accordance with design objectives. Qualitative data such as which prompts produced more effective results, what types of outputs the system provided for specific design inputs, and how the interaction between artificial intelligence and human creativity was established were also included in the process. Finally, existing spatial data were analyzed, and functional, aesthetic, and ergonomic spatial configurations considering user needs were produced. The selected interior spaces were reinterpreted by adapting them to different usage scenarios such as educational spaces, relaxation areas, exhibition spaces, and waiting areas, thereby reconsidering the potential of the spaces. During this process, interventions aimed at enriching user experience through design components such as color, texture, material, furniture layout, and lighting were expected. In addition, at this stage, it was aimed for students to develop their critical thinking, problem-solving, and alternative generation skills, and to actively participate in the creative design process based on spatial reading and reconstruction. The spaces in the study were transformed into six different spaces: a hobby room, gallery and workshop area, cinema, music studio, kitchen, and dressing room.

Results and Discussion

Within the scope of the study, survey studies were first carried out in order to document the existing structure, followed by the use of artificial intelligence-supported methods in the analysis of the obtained data, and finally, applications based on the results of these analyses were conducted. As a result of this three-stage process, both the integration of traditional documentation techniques with modern technologies was achieved and the effectiveness of AI-based approaches in practice was tested. In research articles, the results and discussion section should be written under the same heading.

Stage 1: For each space, survey studies including plan, section, elevation, and detail drawings provided the technical and visual documentation of the existing condition. During this process, the infrastructural basis of the design was established by analyzing the dimensional data of the space, structural elements, material properties, and current usage conditions (Figure 2).

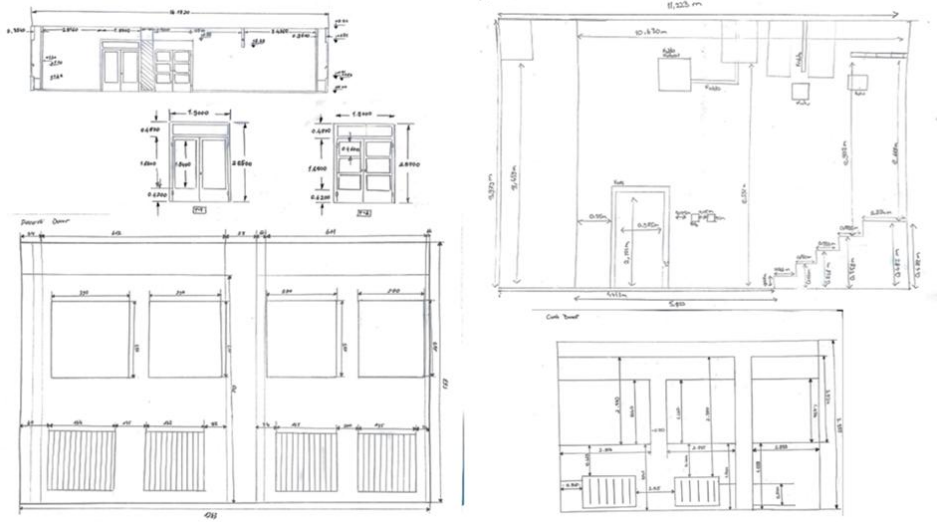


Figure 2. Some survey visuals of six different interior spaces selected by the students within the scope of the study.

The obtained survey outputs formed the basis for the redesign process in the next stage and supported students in comprehending the spaces both physically and functionally. In line with the collected data, the current conditions of the selected spaces were transferred into a digital environment using technical drawing software such as AutoCAD. In these drawings, structural elements such as walls, doors, windows, columns, and flooring, together with functional arrangements, were illustrated. In addition, the volumetric structure of the spaces, lighting conditions, circulation areas, and existing usage forms were analyzed and documented. This stage enabled students to reinforce their measurement and evaluation, spatial perception development, and technical drawing skills, while also allowing the acquisition of analytical data forming the basis of the design process (Figure 3).

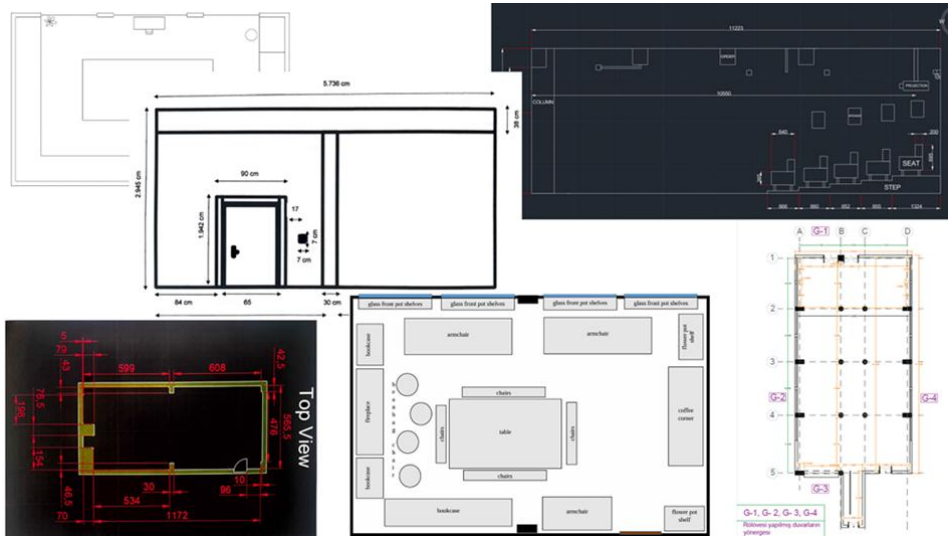


Figure 3. Some AutoCAD visuals of six different interior spaces selected by the students within the scope of the study.

Stage 2: Whether the content of the text-based commands (prompts) directed by the students directly affected/did not affect the quality of the outputs obtained from artificial intelligence revealed the importance of conscious and goal-oriented prompt design. In addition, qualitative data such as which types of prompts produced more/less efficient results and how artificial intelligence tools responded to different design parameters provided important insights into the ways students interacted with artificial intelligence.

Within the scope of the study, artificial intelligence commands applied to the surveyed spaces were systematically used at various stages of the design process. Through text-based commands (prompts) provided to AI-based visualization tools, students created three-dimensional interior space configurations based on the survey data. In this context, first, the dimensions and basic geometry of the space were defined, and space models with clearly determined physical boundaries were produced within the AI environment.

In the following stages, the focus was placed on furniture layout and interior space arrangements; the type, position, and arrangement of furniture were tested through AI outputs in accordance with user scenarios. Students evaluated different layout alternatives by experimenting with various variations of these arrangements. In addition, door and window openings were integrated into the walls using artificial intelligence systems; appropriate solutions for the spaces were produced by controlling the shape, number, and dimensions of the openings.

In the advanced stages of the design process, different scenarios regarding ceiling form, material, and lighting arrangements were developed through artificial intelligence. In this context, the type, position, and distribution of the

light source within the space were evaluated, and lighting solutions aimed at increasing user comfort were investigated. Finally, detailed elements such as accessories and user figures were added, strengthening the perception of scale in the designs and representing usage scenarios in a more realistic manner. Thus, students transformed survey data into AI-supported design commands and developed space-specific, multilayered, and creative solutions.

Stage 3: In the third stage of the study, students analyzed the existing spatial data and developed interior space designs centered on user needs and qualified in terms of functionality, aesthetics, and ergonomics. During the process of refunctionalizing the selected spaces, creative and original solutions were produced in line with different usage scenarios ranging from educational spaces to relaxation areas, exhibition spaces, and music studios. Design components such as color, texture, material, lighting, and furniture layout were addressed using artificial intelligence in a way that enriched user experience, and the potential of the spaces was reinterpreted in different ways (Figure 4).

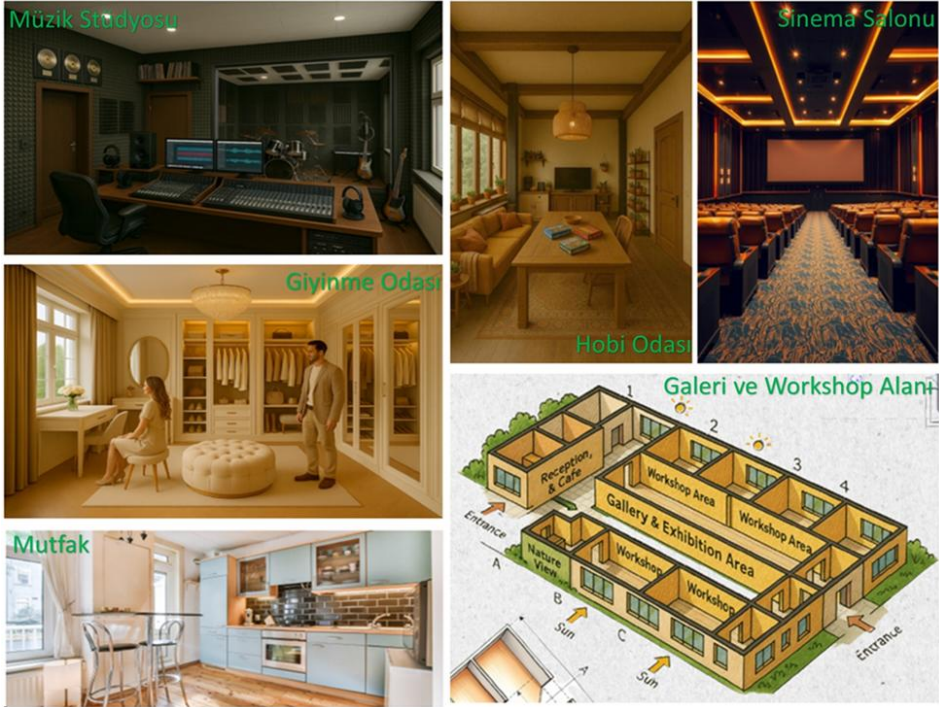


Figure 4. New interior space designs.

As a result, the existing spaces were transformed into six different functional spaces, namely a hobby room, gallery and workshop area, cinema, music studio, kitchen, and dressing room, and were enriched with versatile usage possibilities. This transformation provided a qualified learning experience in which both the

theoretical and practical aspects of the design process were successfully integrated.

Students were expected to reinterpret the spaces both functionally and aesthetically by benefiting from AI-supported data analysis, modeling, simulation, and visualization techniques. Thus, an experimental learning environment was created regarding how artificial intelligence can be integrated into complex design processes requiring both technical knowledge and creativity. This approach contributed to students developing an interdisciplinary perspective by combining traditional design methods with next-generation AI-supported techniques.

The findings obtained from the study revealed that AI-supported tools played a role in supporting students' creativity and accelerating the interior design process. After analyzing the spaces in detail through survey studies, students produced innovative design solutions in terms of functionality and aesthetics while largely preserving the existing physical characteristics of the spaces. During the redesign stage, it was observed that they evaluated the spaces multidimensionally by developing various scenarios, especially regarding user orientation, material selection, and spatial organization.

These findings support studies in the literature indicating that the integration of artificial intelligence technologies into design education enhances creativity and accelerates design processes. Oxman (2017) states that digital design tools encourage creativity and enable the production of more alternatives during the design process, while Gu and Behbahani (2021) emphasize that AI-supported design tools complement the designer's intuitive decision-making processes.

However, the majority of the students evaluated the integration of artificial intelligence tools into the design process as motivating, exploration-oriented, and inspiring. The data obtained throughout the process demonstrated that the interaction established between artificial intelligence and human creativity transformed students' approaches to design, diversified their thinking processes, and particularly improved their ability to generate alternatives. These findings reveal that artificial intelligence can be effectively used as a supportive tool in design education.

The use of artificial intelligence tools accelerated students' design processes, improved their alternative generation skills, and expanded their possibilities for visual expression. However, the limitations of artificial intelligence were also observed during the process. In particular, situations such as context-independent suggestions, technical inconsistencies, and deficiencies in user orientation were critically evaluated by the students. Accordingly, conclusions were drawn that, in addition to the advantages offered by AI as a design tool, more efficient results are produced when it is used together with human creativity and professional intuition.

This stage enabled students to evaluate artificial intelligence not only as a technical tool but also as an active component of the creative process; furthermore, it allowed them to experientially examine the possibilities and limitations of integrating AI into interior design education. These findings are also consistent with various studies in the literature. Dautenhahn (2007) draws attention to the complementary role of artificial intelligence in creative processes, while Boden (2016) emphasizes that AI can be considered a tool that supports rather than imitates creativity. Similarly, Gunkel (2012) points to the ethical and cognitive boundaries of human-machine interaction and discusses the effects of this relationship on design practices. The experiences of the students practically confirm these theoretical approaches.

Conclusions

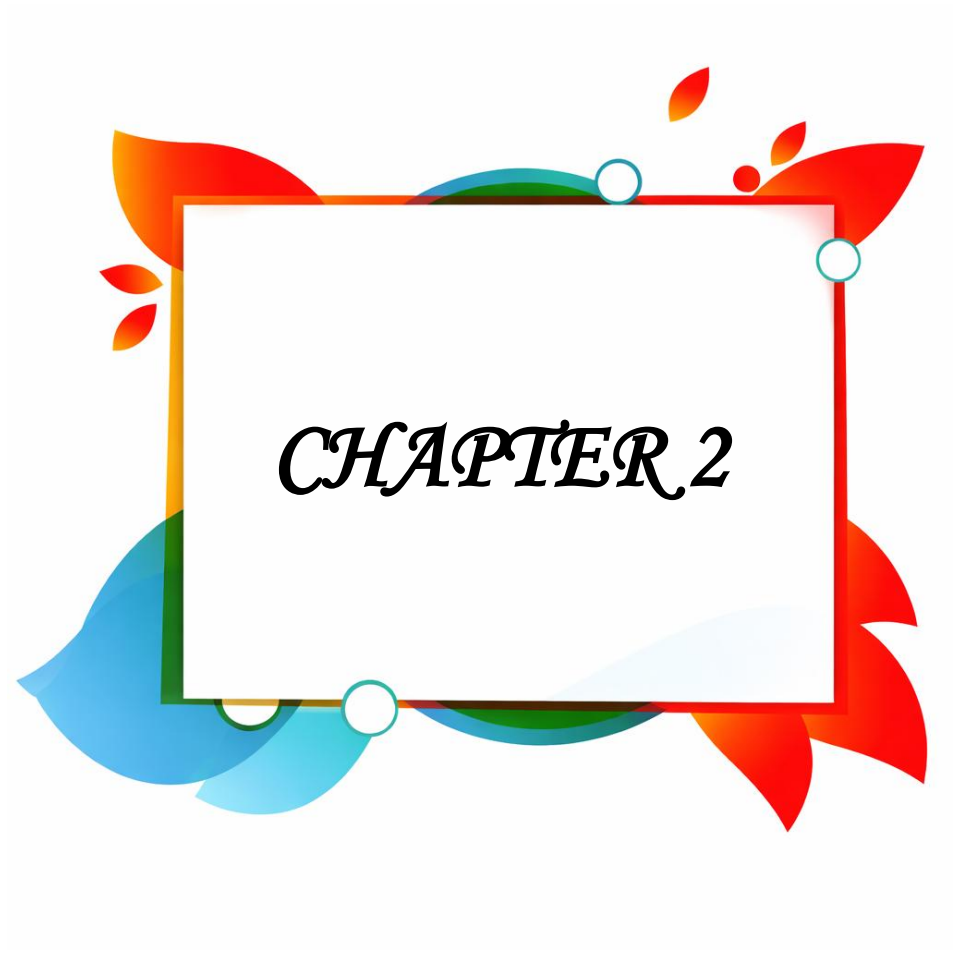
- AI-supported tools accelerate students' design processes and support their creativity.
- Students developed innovative design solutions in terms of functionality and aesthetics by analyzing the spaces in detail while preserving their existing physical characteristics.
- During the redesign stage, multidimensional evaluations were carried out regarding issues such as user orientation, material selection, and spatial organization.
- The integration of artificial intelligence technologies into design education improves students' creative thinking and alternative generation abilities.
- Students evaluated artificial intelligence tools as motivating, exploration-oriented, and inspiring.
- The interaction between artificial intelligence and human creativity transformed students' approaches to design and diversified their thinking processes.
- Artificial intelligence tools have limitations such as context-independent suggestions, technical inconsistencies, and deficiencies in user orientation.
- The most efficient design results are obtained through the combined use of artificial intelligence tools, human creativity, and professional intuition.
- Students evaluated artificial intelligence not only as a technical tool but also as an active component of the creative process.
- The results of the study reveal that artificial intelligence plays a supportive and complementary role in interior design education and are consistent with the theoretical approaches in the literature.

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From Wearable Luxury to Living Space: Fashion Houses, Interior Design and the Spatialisation of Luxury Branding

Emine Seda Erdinler¹

Introduction

According to Kapferer and Bastien (2012), luxury is a product of symbolic value, not just practical value, and of controlled desirability and cultural distance. It is a compelling argument which can explain why luxury fashion houses are expanding from clothing, leather goods and accessories to furniture, tableware, lighting, textiles and entire interior ideas. Dior, Louis Vuitton, Hermès, Fendi, Versace, Armani, Gucci, Dolce&Gabbana, Bottega Veneta, Missoni, Roberto Cavalli and Ralph Lauren are all penetrating the home collection market, indicating that luxury is not just worn on the body these days. It also operates, inhabits and is arranged within the domestic space.

In this research paper, the authors propose that the strategy of luxury fashion houses to diversify with furniture and interiors is not merely a commercial diversification strategy. It is a spatialization of luxury branding which invites consumers to “live in” a brand's symbolic universe. Possession can be a part of the extended self, as Belk (1988) explains and taste can be a signifier of cultural distinction as Bourdieu (1984) demonstrates. In combination, these arguments point towards the possibility that interiors can convey identity, status and social positioning in a manner similar to fashion. But there is risk with this growth too. However, Reddy et al. (2009) caution that when luxury brand extensions are taken too far away from the credible associations of the parent brand, brand meaning is lost. Thus, this research paper explores the three paradigms: maximalist spectacle, minimalist quiet luxury and heritage-led lifestyle world-building, in which luxury fashion houses render their fashion codes into interior design.

Literature Review

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Belk (1988) argues that possessions are not external to identity, because objects can become part of how individuals understand and present themselves. This framework is significant since furniture and domestic products are not passive background items. A chair, sofa, table setting or blanket can be used as a visual extension of the consumer's taste in luxury interiors. Baudrillard (1996) also refers to objects as components of a larger system of signs, implying there is a symbolic and social dimension to objects. This is significant with luxury home collections because a branded armchair or porcelain plate doesn't just offer comfort or use. It also conveys an affiliation with specific aesthetic worlds.

Bourdieu (1984) extends this claim by demonstrating the linkage between taste and cultural capital and social distinction. This attitude gives interiors not a neutral personal option. They can communicate about education, class standing, refinement and lifestyle aspiration. This is particularly evident in luxury furniture as the home is transformed into a space of distinction. It is also important to note that Armani/Casa's more minimalist interiors convey a different type of status statement as compared to Versace Home's more theatrical gold, Medusa and classical references. Brand prominence is one way that Han et al. (2010) can help to explain this difference. The consumers prefer some luxury signs which are loud and recognisable, and some which are subtle and can be only read by the cultured viewers.

The home collections of luxury brands can be understood through the problem which is faced in the process of extension. Reddy et al. (2009) question the extent to which luxury brands can stretch without hurting the brand image. This argument is particularly pertinent as furniture is not part of the same category as fashion, despite the common design elements, materials and lifestyle. As seen by Hennigs et al. (2013), luxury brand extensions have an impact on consumer perceptions of the parent brand and Eren-Erdogmus et al. (2018) claim that the effectiveness of the extension depends on the perceived fit, luxury value and product-category involvement. That is, a home line is most successful when it conveys recognisable home brand codes to a related design field. Hermès can expand to leather furniture and cashmere throws as these are associated to the craft heritage of Hermès. Patterns and fabrics are a way of representing the brand and Missoni can go one step further and expand into home textiles.

Luxury extensions also present a quandary between growth and exclusivity as demonstrated by Margariti et al. (2019). This is the key point of contention that has arisen in fashion houses' entry into interiors. Home collections can be a way for a brand to become more lifestyle relevant, but they can also look like decorative goods when it's just about logos. There is a direct link between luxury fashion brands and furniture design as stated by Codignola (2018), who states that strategic connections created between fashion and furniture enable brands to challenge new cultural and commercial terrain. Therefore, this is a research paper

looking at interiors as a brand extension field, NOT a secondary accessory market.

Research Methodology

Codignola (2018) provides a suitable basis for a qualitative comparative analysis of fashion houses and furniture design because the relationship between the two fields depends on aesthetic association, brand coherence and design credibility. Through comparative brand analysis, this research paper looks at official home collections, product categories, material selection, motifs and visual language and brand narratives. The aim is not to make any commercial comparison among the brands, but to investigate how each of them reinvents the concept of fashion identity in interior room.

Twelve brands have been categorized into three paradigms for analysis. The first is maximalist and expressionist luxury that is embodied by Versace, Gucci, Dolce&Gabbana and Roberto Cavalli. The second is minimalist, purist and quiet luxury, in the form of Armani, Bottega Veneta, Hermès and Dior. The third is heritage, functionality and lifestyle world-building and Louis Vuitton, Fendi, Missoni and Ralph Lauren are all part of that. These categories are not definitive. Several brands overlap. Dior is minimalist in some objects while decorative in tableware for example. However, the typology enables this research paper to compare the transformation of design DNA into domestic environments by different fashion houses.

Why Interiors Matter Now - Market Context

According to Bain & Company and Fondazione Altagamma (2025), global luxury consumption in the various luxury categories is likely to remain broadly stable at €1.44 trillion in 2025. This indicates that luxury is still sizeable and robust, but by no means high-growth. Similarly, the Business of Fashion and McKinsey & Company (2025a) contend that the luxury market has slowed down and is projected to see global luxury sales only grow by 2 to 4% annually from 2025 to 2027. They also indicate that high-spending clients are likely to drive 65-80% of the market's growth until 2027, underlining the critical value of cultivating more robust connections with high-value consumers.

This context in the market explains the importance of interiors. According to Euromonitor International (2025), the luxury value is now being redefined by lifestyle-oriented value, emotional relevance and shifting consumer expectations. Deloitte (2026) also shows the luxury sector shifting toward a more selective landscape where brands must prioritize meaningful growth, rather than expansion. Home collections offer fashion houses more enduring and less season-specific opportunities than ready-to-wear. Unlike a fashion season, a sofa, table, rug or residence concept lasts a bit longer within the consumer's life.

Commercial value is also given by the luxury furniture market. According to Grand View Research (2025), the worldwide luxury furniture market was valued at USD 31.06 billion in 2024 and is expected to grow 4.2 percent CAGR, reaching USD 39.79 billion by 2030. Looking more broadly at the space, Savills (2025) predicts that branded residential developments will increase by 19 per cent year-on-year from 764 in December 2024 to 910 by the end of 2025. Resilience in the décor, design and lifestyle industry is reported by Maison&Objet (2025) which surveyed 1,183 professionals in March and April 2025. So, the fashion houses' venture into interiors is to be understood as both cultural and strategic. It takes luxury beyond ownership of the product to a lived environment.

Maximalist and Expressionist Interiors

Han et al. (2010) show that luxury can signal status through high brand prominence, and this logic is clearly visible in maximalist fashion interiors. Versace Home, Gucci Décor, Dolce&Gabbana Casa and Roberto Cavalli Home see the home as a stage. The way their interiors are built is not supposed to disappear into the background. They make the brand easily recognisable with the help of colour, motif, historic reference and surface intensity.

The furniture and objects of Versace's home universe interpret the codes of the classical and theatrical house. With reference to the heritage, to recognisable house codes and expressive interior forms, Versace (2026) shows its Home Collection 2026. The Medusa, Greca and Barocco codes act as domestic status signs. According to Baudrillard (1996), objects can be interpreted as symbols of power and sensuality as well as a recognisable luxury. With Gucci, it's a different story, but it's still maximalist. According to Gucci (2026.) Décor and Lifestyle is an eclectic area of furniture, tableware, textiles, wallpaper and leisure objects that relate to the visual language of the house. The outcome is not as palacey as Versace, but more eccentric and collectory.

Dolce&Gabbana Casa is an interior brand that conveys stories based on Italian lifestyle and the Mediterranean. Dolce&Gabbana (2026) shows Casa by means of furnishing and accessories that are intended to change domestic area into unique environments. With its visual codes from Sicilian and Mediterranean tradition these make the home festive and regional; it relies on narration. Roberto Cavalli Home takes maximalism to animalier, exotic and sensual heights. Roberto Cavalli (2026) offers its home world at the Milan Design Week in the form of a solid connection between nature, surface and metropolitan energy. It helps uphold the brand's glam-rock inner personality.

What makes these brands strong is that they are easily recognized. However, Reddy et al. (2009) and Margariti et al. (2019) caution that extension can be taken too far, or too far away from design credibility, and become a risk for recognisability. For these maximalist interiors to be effective, the ornate elements

need to fit in with the existing fashion of the house, as illustrated in Figure 1 below.



Figure 1: Maximalist interior codes of luxury – visible motifs, colour saturation and theatrical brand recognition. Source: Archiscene (2021)

Minimalist, Purist and Quiet Luxury Interiors.

According to Kapferer and Bastien (2012), the condition of luxury is related to symbolic distance and controlled desirability. Their interiors are based on proportion, material, craft and cultural literacy. This would be considered as lower brand prominence (Han et al., 2010) because the brand is not indicated directly, but rather by fine codes.



Figure 2: Armani Casa Collection. Source: Armani Casa (2026)

As illustrated in Figure 2 above, Armani/Casa (2026) presents its interiors in the nuanced language of minimal lines, harmonious proportions and sleek material finishes. As Bourdieu (1984) would put it, this is a sort of distinction of understatement. The Armani interior "mentions" to the consumer that he gets the idea of proportion and atmosphere. Bottega Veneta is also a part of this quiet

luxury paradigm. Bottega Veneta (2026.) offers home objects as “Art of Living” and the house's overall look and feel is linked to leatherwork and understated luxury. Bottega Veneta's interiors therefore expand on the material technique and tactile recognition, and not on obvious brand visibility.

Hermès is an example of craft legitimacy. Hermès (2026) has furniture, lighting and rugs, and a broader universe of the home is created around material quality, craft and controlled form. As the brand already has leather connotations, as well as equestrian and handcrafted elements, furniture and home objects seem like natural extensions. The new category transmits the already existing luxury value to a related area, and this is what Eren-Erdogmus et al. (2018) would call strong perceived fit.

Practically, Dior Maison is basically decorative than Armani or Bottega Veneta, but it still fits in here due to its domesticity being controlled, refined and ritualistic. Dior (2026) showcases Dior Maison via tableware, house collections, cannage and toile de jouty. This makes the house an art de vivre house and not a noisy branded house. The table settings of Dior Maison are just as luxurious as its furniture, conveying luxury intimacy and sociality through dining rituals, as pictured in Figure 3.



Figure 3: Domestic ritual, cannage and tableware: luxury expression at Dior Maison and art de vivre. Source: Dior (2026.).

One huge benefit of quiet luxury interiors is durability. They are not so much subject to the fashion of motifs, and more to the material, craft and proportion. However, the downside is the codes are not as noticeable to consumers that are not familiar with the brand. So, luxurious quietness is as much about knowledge about culture as it is about price.

Heritage, Functionality and Lifestyle World-Building

While Belk (1988) states that possessions contribute to the formation of the self, some brands are able to build a lifestyle atmosphere. Not only do Louis Vuitton, Fendi, Missoni and Ralph Lauren translate their motifs into home products. They construct spatial narratives about travelling, Roman craft, textile identity and American living. That's where fashion house interiors get world-building.



Figure 4: LV Art of Living Luxury Home Furnishings Source: LV (2026.).

According to Louis Vuitton (2026), Objets Nomades is a designer collection of luxury home décor items such as lamps, tables and collectible objects (Figure 4). This gives credibility to the extension by reference to the history of travelling trunks in and from the house. The furniture is not random, it is a highly selected choice. It translates the art of travel into movable, sculptural and collectible design objects. On the other hand, Fendi Casa (2026.) showcases a full spectrum collection that is inspired by savoir-faire, craftsmanship and innovation from living through dining to sleeping and outdoor collections, as shown below in Figure 5. With this, Fendi boasts one of the best full-house collections of all the fashion houses. Its interiors are believable given the brand's already strong connections with leather and fur, Roman modernity and material luxury.



Figure 5: Fendi Casa, Fendi F Affair by Controvento Source: Fendi (2026).

According to Hennigs et al. (2013), luxury extensions can alter the consumers' perception of the parent brand, and perhaps Fendi Casa will help to change the consumers' impression of Fendi as a fashion house to a design-led lifestyle maison. Missoni Home practices textile continuity. According to Missoni (2026.), the home collection is made with cushions, throws, poufs, tableware and decorative objects that represent the colour and pattern of the brand. The zig zag and chromatic textile codes flow from body to sofa, rug and wall. This is a good illustration of transfer extension because the material logic of fashion and interior design are similar.

The most entire lifestyle instance may be Ralph Lauren Home. Ralph Lauren (2025) showcases a Canyon Road line that it describes as "inspired by the American West" and showcases natural fabrics like rustic oak and hand-burnished saddle leather. It's not just about selling furniture. It creates a cinematic universe of American gentility, ranch tradition and homeownership dreams.

This paradigm might be the most stable one as the brand extensions are not only decorative. They link the product function to a greater story of heritage. But a very important question remains. Luxury brands are increasingly entering into whole environments, as Savills (2025) demonstrates it through the development of branded residences. This could further engrain consumer loyalty but it could also make the living space a very commercialized brand ecosystem.

Discussion

The three paradigms indicate that luxury interiors are not necessarily one single trend. Different strategies to convert a brand identity into space. Oversized brands make instant branding. Quiet luxury brands establish material and cultural recognition. Heritage defines brands with a story and an aura.

The most extreme and maximalist like Versace, Dolce&Gabbana, are strong examples of interiors that are visually powerful as their fashion codes are already theatrical. However, what they run the risk of is having the residence become "over-branded". This is similar to Reddy et al., (2009) caution about luxury extensions, which must not be 'just brand exploitation'. Meanwhile, Armani, Bottega Veneta and Hermès demonstrate that luxury can be spatialized with restraint. Almost the reverse is the case with their risk. The design can be subtle, requiring prior knowledge for its brand meaning. Han et al. (2010) can explain this difference by the following: visible and inconspicuous status signalling.

It is at the crossroads here where heritage, or heritage-led brands, can find the best solution. Louis Vuitton, Fendi, Missoni and Ralph Lauren take brand DNA and make it functional and storytelling, for the interiors. Supporting this reading, Codignola (2018) argued that fashion-furniture relationships are more efficient when it is a strategic one, not superficial. Some brands are found to have a strong logic of categories: Missoni's textiles, Louis Vuitton's travel objects, Fendi's material luxury and Ralph Lauren's lifestyle world. However, these interiors are not just costly products, as in Bourdieu's (1984) vocabulary, these are systems of tastes organized in a hierarchical manner.

Strategically relevant in the market context. According to Bain & Company and Fondazione Altagamma (2025), The Business of Fashion and McKinsey & Company (2025a), Deloitte (2026) and Euromonitor International (2025), the luxury sphere is becoming more discerning and brands need to prove their value and build their relevance. Additionally, McKinsey & Company and Business of Fashion (2025b) demonstrate that the rules of fashion growth are shifting, making for the time being, and possibly for the long run, the concept of durable lifestyle touchpoints more appealing. Furniture and tableware can help establish more enduring emotional connections with consumers, as can branded interiors.

Conclusion

According to Kapferer and Bastien (2012), the maintenance of symbolic power is crucial for luxury; and this research paper has illustrated the significance of interiors as a pivotal factor of this symbolic power. In this shift from luxury to wearables, to space to live, we see a general trend that fashion houses are no longer just dressing the consumer. They more and more construct the consumer's domestic space, social practices and imagination of life.

Home objects are important to identity as explained by Belk's (1988) extended self and interiors can function as cultural distinction as explained by Bourdieu's (1984) theory of taste. But, there is an important warning from brand extension theory. Only when extensions provide a fit, exclusivity and symbolic coherence, they are strong luxuries, as demonstrated by Reddy et al (2009); Hennigs et al (2013); Eren-Erdogmus et al (2018); Margariti et al (2019). Hence, Hermès craft, Louis Vuitton travel, Missoni textiles, Fendi materiality and Ralph Lauren lifestyle look more believable than just a logo transfer.

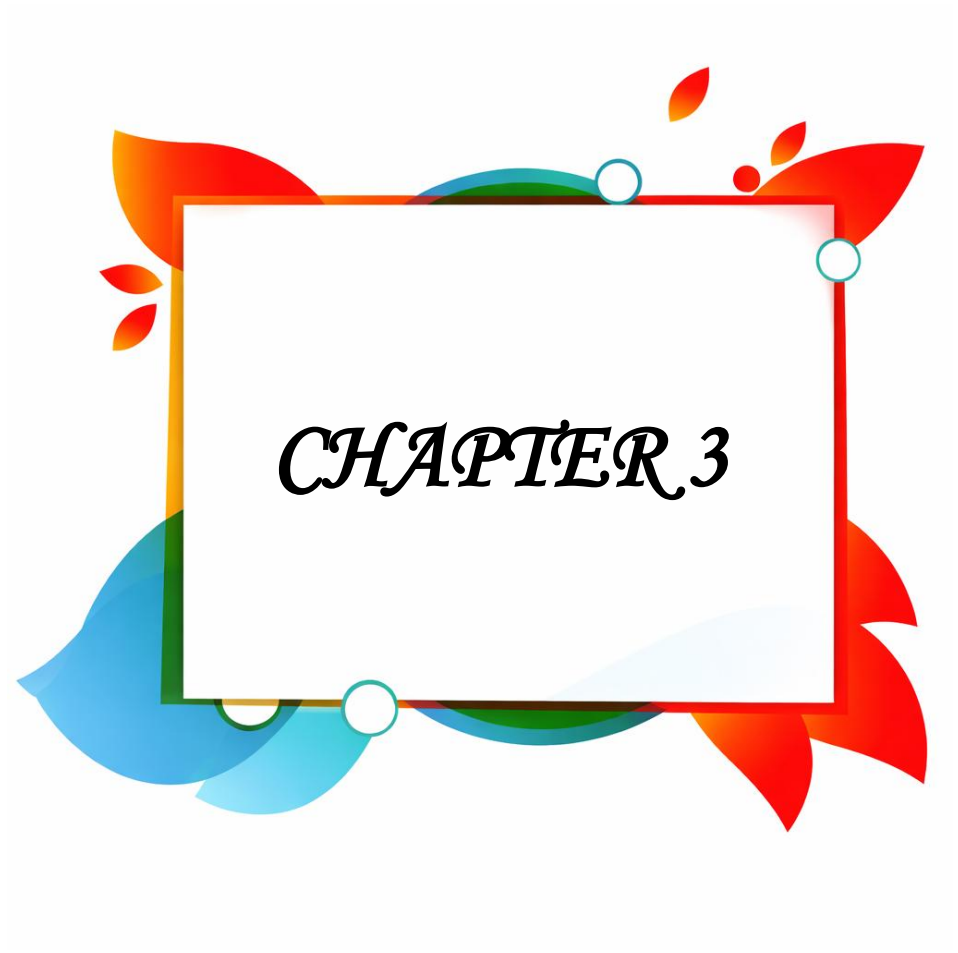
In conclusion, the development of luxury brands in interiors by luxury fashion houses can be interpreted as the spatialisation of luxury brands. Maximalist brands transform the home into a spectacle, quiet luxury brands into refined cultural capital and heritage-led brands into a lifestyle world-building. Home collections have strategic value in the 2025/2026 luxury context where growth is more modest and consumers are more discerning. But success relies on whether the object feels like it's a natural extension of the house's aesthetic world. Luxury interiors are thus not supposed to be furniture. They are places of identity, taste and belonging that are branded.

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Ecological, Economic, and Sustainability Dimensions of Local Communities' Perceptions of Non-wood Forest Products: A Case Study for Bucak

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1. INTRODUCTION

Forests are now recognized not only as communities of trees, but also as complex socio-ecological systems that must be considered in conjunction with the people living within and around them (MEA, 2005; Wolfslehner et al., 2019). Forest resources play a key role, either directly or indirectly, in sustaining the livelihoods of approximately 1.6 billion people worldwide (Mahmoud, 2016). Approximately 1.2 billion of these are dependent on trees and forest resources for food and income, especially in developing countries (Vidale et al., 2015).

Non-wood forest products (NWFP), which are among these multifaceted benefits, encompass biological resources derived from forest ecosystems that are made available for human use except for lumber. Medicinal and aromatic plants, mushrooms, fruits, resins, essential oils, seeds, and similar plant products, as well as various animal products, are considered within this scope (Beer and McDermott, 1989; Balcı, 2011; Lovric et al., 2020). NWFP's offer potential for use in many fields, such as food, health, cosmetics, and industry, thereby creating economic value and contributing to social well-being. Many medicinal plants collected from nature have served as a source for modern drug development efforts and have demonstrated significant potential in the treatment of various diseases (Siram et al., 2023; Akram et al., 2023; Asha et al., 2020).

The diversity and economic value of NWFP are closely linked to a country's floristic richness. According to the World Health Organization, approximately 20,000 plant species worldwide are used for various purposes, and about 10% of

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these are traded (Sarı and Oğuz, 2000; WHO, 2010). Türkiye is among the countries with high plant diversity due to its location at the intersection of the Mediterranean, Euro-Siberian, and Iran-Turan floristic regions. This situation allows for the natural growth of numerous plant species with medicinal, aromatic, and economic value (Bayram et al., 2010; Özdemir and Özkan, 2016). According to the General Directorate of Forestry's 2023 forestry statistics, Türkiye's Forest cover has reached approximately 23.4 million hectares (GDF, 2025). The flora of Türkiye includes 1,251 genus and over 12,000 taxa belonging to 174 families (Davis et al., 1988; Güner et al., 2012; Terzioğlu et al., 2021).

Bucak Region, which is the subject of this study, exhibits transitional characteristics between the Mediterranean and continental climates, allowing for the coexistence of different ecological conditions. This situation paves the way for the diversification of natural vegetation and the widespread utilization of non-wood forest products. However, sustainable management of these resources and the effective utilization of their economic potential are largely dependent on the local population's level of knowledge, usage patterns, and their awareness of non-wood forest products. Therefore, determining how non-wood forest products are perceived and valued by local communities is important for the sustainable management of these resources and for enhancing their contribution to regional development.

This study aims to identify the perceptions, usage patterns, and levels of awareness among individuals living in the Bucak region regarding the ecological and economic value of non-wood forest products.

2. MATERIALS AND METHODS

This study was conducted within the boundaries of the Bucak district. The study area is located between approximately 37°30'–37°45' north latitude and 30°20'–30°40' east longitude (Figure 1). The region's average annual temperature is 13.1 °C, and the average annual precipitation is approximately 910 mm (Climate Data, 2026). According to the Köppen–Geiger climate classification, the region belongs to the Csa climate type, which is characterized by hot, dry summers and mild, rainy winters (Rubel et al., 2017).

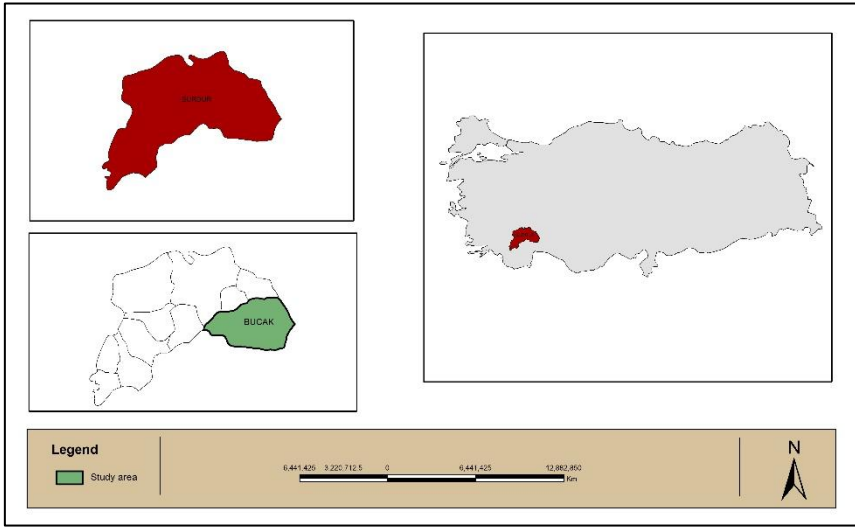


Figure 1. Map of the study area

Data Collection

The survey method was used as the data collection tool in this study. The survey form consists of questions designed to determine the participants' demographic characteristics, as well as statements aimed at measuring their views on the economic value, ecological importance, sustainable use, and contribution to local development of non-wood forest products. A 5-point Likert scale was used in the survey form to evaluate the participants' views.

Sampling and Data Collection Process

The study sample consists of 100 people living in the Bucak region. The survey was conducted through face-to-face interviews with the participants, and the data collected were analysed. Participation in the study was voluntary, and participants were informed about the purpose of the study.

Data Analysis

The data obtained from the surveys were entered into an electronic format and analysed using R Studio software. First, the dataset was checked and prepared for analysis. A Cronbach's alpha reliability analysis was conducted to determine the internal consistency of the scale used in the study. Frequency distributions were used to evaluate the participants' demographic characteristics. To determine participants' views on non-wood forest products, descriptive statistics were calculated, and the minimum and maximum values, as well as the mean and standard deviation, were determined for each statement.

3. RESULTS

The Cronbach's alpha coefficient was calculated to determine the reliability of the survey form used in the study. A Cronbach's alpha coefficient approaching 1 indicates an increase in the internal consistency of the items on the scale (Yang and Green, 2011). In this study, the Cronbach's alpha coefficient was found to be 0.803. This value indicates that the scale has a high level of internal consistency and can be used as a reliable measurement tool. A total of 100 people living in the Bucak region participated in the study. Findings regarding the participants' demographic characteristics are presented in Table 1.

Table 1. Demographic characteristics of the participants

Variable		Frequency (n)
Gender	Male	53
	Female	47
Education Level	Elementary/Middle School	37
	High School	37
	Bachelor's/Associate's Degree	38
Age	18-30	41
	31-45	36
	46-60	21
	60+	2

An examination of Table 1 reveals that 53% of the participants were male and 47% were female. It was also determined that individuals from different age groups and educational levels participated in the study. This indicates that the sample consists of participants with diverse sociodemographic characteristics.

In the study, a scale consisting of statements regarding economic value, ecological importance, sustainable use, level of awareness, and contribution to local development was used to assess participants' views on non-wood forest products. Descriptive statistics were used to analyse the participants' responses to these statements. In this context, the minimum and maximum values, as well as the mean and standard deviation, were calculated for each statement. The results are presented in Table 2.

Table 2. Descriptive statistics on participants' views regarding non-wood forest products

Question	N	Minimum	Maximum	Mean	Std. Deviation
1	100	2	5	4.88	0.477
2	100	3	5	4.59	0.570
3	100	1	5	4.02	1.054
4	100	1	5	3.77	1.246
5	100	1	5	4.47	0.893
6	100	3	5	3.99	0.745
7	100	2	5	4.38	0.749
8	100	2	5	4.74	0.562
9	100	1	5	4.00	1.119
10	100	1	5	3.76	1.156
11	100	3	5	4.45	0.642
12	100	1	5	2.92	1.032
13	100	1	5	4.61	0.723
14	100	3	5	4.56	0.656
15	100	2	5	4.54	0.744
16	100	1	5	4.07	1.027
17	100	3	5	4.65	0.642
18	100	1	5	4.13	0.950
19	100	2	5	4.27	0.827
20	100	1	5	4.44	0.891
21	100	1	5	4.27	0.962
22	100	2	5	3.89	1.014

An analysis of the participants' views on non-wood forest products reveals that the highest average score (4.88 ± 0.48) was obtained for the statement "Non-wood forest products are found in the Bucak forests." This result indicates that the participants have a high level of awareness regarding the presence of non-wood forest products in the region. Similarly, the statements "It is important to harvest non-wood forest products without harming nature" (4.74 ± 0.56), "Providing training and seminars to increase the value of non-timber forest products is beneficial" (4.65 ± 0.64), and "Improper harvesting of non-wood forest products damages biological diversity" (4.61 ± 0.72) also received a high level of agreement. These findings indicate that participants are concerned about the sustainable use and conservation of non-wood forest products.

When the economic factor was evaluated, participants expressed a high level of agreement with the statements "Non-wood forest products are an important source of income for the local population" (4.59 ± 0.57) and "The processing of non-wood products and their transformation into value-added products is important for regional development" (4.56 ± 0.66). This indicates that individuals living in the Bucak region are aware of the economic potential of non-wood forest products and believe that these products can contribute to local development.

In contrast, the lowest average score was recorded for the statement “We are sufficiently informed about non-timber forest products in Bucak” (2.92 ± 1.03). Furthermore, the relatively low average score (3.76 ± 1.16) for the statement “I have knowledge about sustainable methods for collecting non-wood forest products” indicates that, although participants are aware of the importance of non-wood forest products, they do not consider the training and information activities to be sufficient.

4. DISCUSSION AND CONCLUSION

While timber production is generally regarded as the primary objective in forest resource management, non-wood forest products have long been overlooked (Wiersum, 1995). Yet, non-timber forest products are among the important goods and services provided by forest ecosystems. However, due to a lack of recognition of their economic value and difficulties in reliably determining their quantities, they are often underrepresented in assessments of ecosystem services (Maes et al., 2011, 2012; Wiersum et al., 2018). However, international studies have shown that NWFPs make significant contributions to food supply, food security, income generation, and traditional medical practices (WHO, 2002; Babulo et al., 2009; Asfaw et al., 2013; Ickowitz et al., 2014; Shackleton and Pandey, 2014; Rowland et al., 2017; Rasolofson et al., 2018). These products, which play a key role in the livelihoods of rural communities in particular, are extensively harvested by women and children, thereby making significant contributions to household economies in regions where alternative sources of income are limited (Dafa-Alla and Eltayeb, 2014; Abdelrahim, 2015; Ibrahim et al., 2015; Younis et al., 2018). However, the excessive harvesting of NWFPs for commercial purposes can have negative impacts on biodiversity and the sustainability of forest resources (Taghouti et al., 2021). Therefore, it is necessary to evaluate both biological and economic factors in the management of NWFPs and to develop sustainable production and harvesting practices (Ghanbari et al., 2020).

This study has shown the levels of perception and awareness regarding NWFPs among individuals living in the Bucak region. The results indicate that participants are aware of the economic and ecological importance of NWFP and believe that these products make significant contributions to local development and rural income sources. Furthermore, the participants’ high level of agreement with statements regarding the sustainable use of NWFP and the conservation of biodiversity indicates that environmental awareness is well-developed among the

local population. However, the fact that participants do not consider current information campaigns regarding NWFPs to be sufficient highlights the need for educational and outreach efforts in this area.

The initiatives carried out by the General Directorate of Forestry, as part of the ORKÖY support program, aim to both improve the well-being of forest villagers and reduce pressure on natural resources. However, to increase the effectiveness of these initiatives, it is necessary to expand educational and awareness-raising activities aimed at improving the local population's level of knowledge. In conclusion, it has been determined that individuals living in the Bucak region have a positive perception of NWFPs and are aware of the economic and ecological importance of these products. However, there are gaps in their knowledge regarding sustainable use practices and existing support mechanisms. For this reason, increasing training activities for NWFPs, developing high-value-added products, and ensuring more effective participation by local communities in sustainable resource management will contribute both to supporting rural development and to the sustainable use of forest resources.

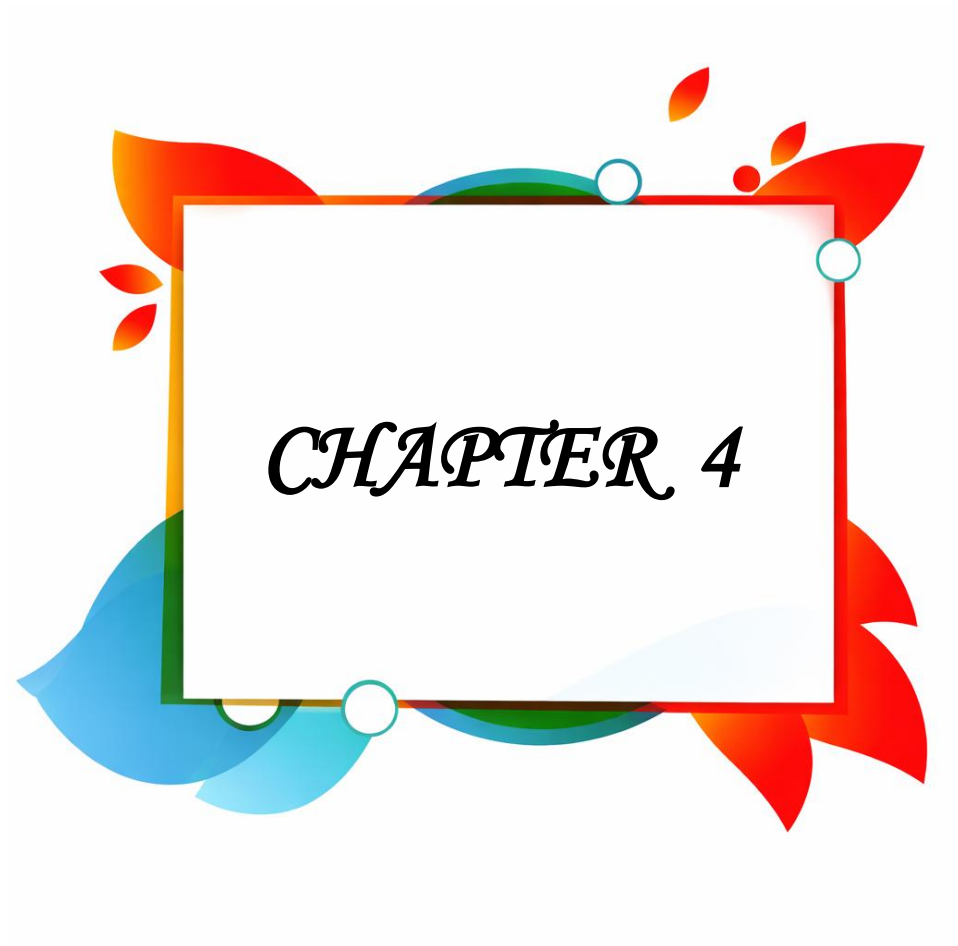
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Behavioural Adaptation Strategies of Crab Species Inhabiting Lagoon Ecosystems

Asude Atala¹ & Seil Acar²

1. INTRODUCTION

Lagoon ecosystems are shallow coastal water bodies partially isolated from the open sea by sand barriers or coastal spits. These transitional environments function as buffer zones between terrestrial and marine systems, forming highly distinctive habitats characterised by elevated biological productivity, substantial nutrient inputs, and highly variable physicochemical conditions (Healy, 1997; Li et al., 2020). Although lagoons account for only 13% of the world's coastlines, they represent critical areas for the feeding, shelter, and reproduction of numerous marine organisms (Yucel-Gier et al., 2018; Botello et al., 2018).

Within these ecosystems, decapod crustaceans occupy key positions in the food web, functioning simultaneously as predators and prey (Farina et al., 1997). Members of the family Portunidae are, in particular, effective predators of bivalve, polychaete, and gastropod communities, and play a regulatory role in ecosystem functioning (Cilenti et al., 2014). The high variability of abiotic factors such as temperature, salinity, and dissolved oxygen in lagoons directly challenges the behavioural flexibility and physiological adaptations of these organisms.

This chapter examines the behavioural adaptation strategies of three crab species prominent in Turkish and Mediterranean lagoons: the Mediterranean green crab *Carcinus aestuarii* (Nardo, 1847), the blue crab *Callinectes sapidus* (Rathbun, 1896), and the European green crab *Carcinus maenas* (Linnaeus, 1758). These three species constitute a suitable group for comparative analysis owing to their wide tolerance ranges, documented lagoon distributions, and their influences on the food web.

Section 2 addresses the general characteristics of lagoon ecosystems, their distribution in Trkiye, and their legal protection status. Section 3 introduces the taxonomy, morphology, distribution, and ecological roles of the species under investigation. Section 4 provides a detailed examination of behavioural

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adaptation mechanisms. Section 5 presents a comparative assessment of the three species, and Section 6 offers conclusions and recommendations.

2. GENERAL INFORMATION: LAGOON ECOSYSTEMS

2.1. Definition and Formation of Lagoons

Lagoons are defined as shallow, enclosed or semi-enclosed coastal water bodies partially separated from the sea by a sand or gravel barrier such as a coastal spit, delta, or barrier island (Obi et al., 2016). Typically with average depths of approximately 2 metres, lagoons are continuously renewed by tidal processes, riverine inflow, and marine water exchange. This hydrological connectivity exerts a determining influence on their salinity, temperature, and nutrient equilibrium.

With respect to formation mechanisms, lagoons may arise through the deposition of sand and gravel by coastal currents forming barrier features, through the inundation of coastal valleys consequent upon sea-level rise, or through the enclosure of isolated water pockets by deltaic ridges. These wetlands, constituting transitional zones between marine and terrestrial environments, share ecological characteristics with estuaries whilst remaining distinct from them owing to differences in morphological connectivity (Healy, 1997).

2.2. Physicochemical Characteristics

The most distinctive feature of lagoons is the pronounced seasonal and diurnal variability of their physicochemical parameters. Due to their shallow and enclosed nature, water temperatures can rise and fall far more rapidly than in open seas; summer water temperatures exceeding 30°C have been recorded in Turkish lagoons (Acar, 2018). Salinity values may fluctuate across a wide range (0–45 psu) depending on precipitation, evaporation, and the degree of marine connectivity.

Dissolved oxygen (DO) concentrations may decline to critical levels during summer as a consequence of elevated temperatures and high organic loading, with hypoxic and even anoxic conditions developing particularly in bottom waters. This situation constitutes a serious physiological stressor for the majority of benthic fauna. pH, light transparency, sediment composition, and nutrient (nitrogen and phosphorus) concentrations are among the principal abiotic factors governing the functioning of lagoon ecosystems.

2.3. Biological Significance and Faunal Composition

Despite accounting for only 13% of the world's coastlines, lagoons hold disproportionate importance with respect to biological diversity (Yucel-Gier et al., 2018). Serving both as habitats and migratory junctions for primary producers, benthic invertebrates, fish, and waterbirds, lagoons are also significant areas for fisheries and aquaculture (Pearce and Crivelli, 1995). Faunal and floral

composition are directly related to meteorological conditions, the degree of water circulation, nutrient indices, and temperature and salinity variables.

2.4. Lagoons in Türkiye

According to systematic classification, a total of 112 lagoons have been identified in Türkiye: 16 along the Black Sea coast, 36 along the Marmara Sea coast, 31 along the Aegean coast, and 29 along the Mediterranean coast, with a total surface area of 38,870.6 hectares (Ekinci and Bayrak, undated). The largest lagoon in Türkiye is the Akyatan Lagoon in Adana Çukurova, covering 5,126.4 hectares. The Çardak Lagoon, situated on the shore of the Çanakkale Strait, represents an important research site for studies of various decapod species, most notably *Carcinus aestuarii* (Acar, 2018; Acar and Ateş, 2020).

2.5. Legal Protection Status of Lagoons

Lagoons and wetlands are afforded international protection under the Ramsar Convention of 1971. Commitments regarding biological diversity were further consolidated through the Convention on Biological Diversity (CBD), signed in Rio de Janeiro in 1992 (Acar, 2018). Türkiye ratified the Ramsar Convention in 1994, and numerous lagoons are consequently afforded international protection status. Increasing anthropogenic pressures and the environmental transformations associated with climate change pose serious threats to Turkish lagoons (Aykır et al., 2022).

3. SPECIES UNDER INVESTIGATION

3.1. *Callinectes sapidus* Rathbun, 1896 — Blue Crab

3.1.1. Taxonomic Position and Morphology

Class: Malacostraca; Order: Decapoda; Family: Portunidae; Genus: *Callinectes*; Species: *C. sapidus* Rathbun, 1896. The blue crab is readily identified by its distinctively blue–green chelipeds and broad, flattened carapace. In adult individuals, carapace width may reach up to 230 mm. The paddle-like modification of the last pair of walking legs confers effective swimming capacity upon this species — an adaptation common to all members of the family Portunidae.

3.1.2. Geographical Distribution

Callinectes sapidus occurs naturally along the Atlantic and Gulf coasts of North America, distributed along an extensive coastal range extending from Canada to Argentina. It has become established as an invasive species along European and Mediterranean coasts. In Türkiye, the first records were reported from Düzce and Zonguldak on the Black Sea coast in 2013 (Yağlıoğlu et al., 2014), subsequently spreading rapidly along the Aegean and Mediterranean coasts and forming significant populations (Harlıoğlu et al., 2018).

3.1.3. Habitat and Ecology

Distinguished by high ecological plasticity, this species is capable of inhabiting diverse coastal environments including estuaries, salt marshes, mangroves, and lagoons (Azra et al., 2020). By virtue of its euryhaline and eurythermal constitution, it can survive across salinity ranges of 0–35 psu and temperature ranges of 5–35°C. As an aggressive benthic predator, *C. sapidus* exerts dominant feeding pressure on bivalves, polychaetes, and small crustaceans (Lipcius et al., 2007). Global catch quantities approximated 75,000 tonnes in 2021, generating production valued at approximately USD 234.8 million (FAO, 2024).

3.2. *Carcinus aestuarii* Nardo, 1847 — Mediterranean Green Crab

3.2.1. Taxonomic Position and Morphology

Class: Malacostraca; Order: Decapoda; Family: Portunidae; Genus: *Carcinus*; Species: *C. aestuarii* Nardo, 1847. Previously described as *Carcinus mediterraneus*, this species was reclassified as distinct from the Atlantic species *C. maenas* by Yamada and Hauck (2001) on the basis of morphometric analyses. Carapace width generally ranges between 40 and 60 mm.

3.2.2. Geographical Distribution

Carcinus aestuarii is widely distributed along all Mediterranean coasts and has also been recorded in the Black Sea, the Sea of Azov, and the Canary Islands (Fischer et al., 1987; Yamada and Hauck, 2001). In Türkiye, dense populations are found in lagoon and coastal areas around the Çanakkale Strait, particularly in the Çardak Lagoon (Acar, 2018).

3.2.3. Habitat and Ecology

Carcinus aestuarii is primarily distributed in lagoons and semi-enclosed coastal areas but is also capable of inhabiting rocky shorelines and sandy substrates. Studies conducted by Matozzo et al. (2011) demonstrated that temperature fluctuations elicit pronounced cellular and biochemical responses in this species. It has also been employed as a sentinel species in environmental pollution biomonitoring studies (Acar, 2024).

3.3. *Carcinus maenas* Linnaeus, 1758 — European Green Crab

3.3.1. Taxonomic Position and Morphology

Class: Malacostraca; Order: Decapoda; Family: Portunidae; Genus: *Carcinus*; Species: *C. maenas* Linnaeus, 1758. This species, with a maximum carapace width of approximately 95 mm, displays a wide colour range extending from green to orange. It has been listed by the IUCN among the 100 worst invasive species in the world (Young and Elliott, 2019).

3.3.2. Geographical Distribution

Carcinus maenas is native to the Eastern Atlantic and Western European coasts, ranging from North Africa to Scandinavia. However, owing to its high phenotypic flexibility, it has successfully established itself in numerous non-native regions including the Northwest Atlantic, Northeast Pacific, Australia, Argentina, and South Africa (Yamada and Hauck, 2001; Roman and Palumbi, 2004). Records from Turkish coasts remain very limited.

3.3.3. Habitat and Ecology

Carcinus maenas is commonly found in bays, estuaries, and harbours, but is intolerant of the vigorous wave action characteristic of exposed open coasts. As an aggressive omnivore, this species consumes a broad range of benthic groups including bivalves, gastropods, polychaetes, and crustaceans (Le Calvez, 1987; Elner, 1981). In regions where it has established, it has been documented to cause significant declines in populations of commercially important species such as the soft-shell clam *Mya arenaria* (Glude, 1955; Grosholz et al., 2000).

4. BEHAVIOURAL ADAPTATION STRATEGIES

4.1. Temperature and Salinity Tolerance

The success of crab species inhabiting lagoon ecosystems is directly contingent upon broad thermal and osmotic tolerance ranges. *Callinectes sapidus* possesses the widest physiological tolerance of the three species. With respect to salinity, it is capable of surviving across a broad range extending from near-freshwater conditions (~0 psu) to approximately 35 psu, maintaining internal salt–water balance through active osmoregulatory mechanisms. Its temperature tolerance spans 5–35°C.

Carcinus aestuarii has developed a robust capacity for tolerance to temperature and salinity fluctuations. Experimental studies conducted by Matozzo et al. (2011) demonstrated that temperature elevation induces changes in enzymatic activity levels and oxidative stress parameters in this species. It remains active within temperature ranges of 8–34°C and salinity ranges of 5–40 psu.

The phenotypic flexibility of *Carcinus maenas* is the principal determinant of its invasive success. Adult individuals in particular can survive across extremely wide ranges including temperatures of 0–33°C and salinities of 4–52 psu (Young and Elliott, 2019). However, the optimum conditions required for reproduction and larval development fall within a considerably narrower range, thereby limiting the species' spread into tropical and cold-water regions.

4.2. Hypoxia Response

During summer months, the rise in water temperature and elevated organic loading in lagoons causes dissolved oxygen concentrations to fall below critical thresholds. *Callinectes sapidus* responds to low-oxygen conditions through several mechanisms: accessing oxygen from the air at the air–water interface, migrating to surface waters containing higher dissolved oxygen, or retreating from the lagoon altogether. *Carcinus aestuarii* has been observed to increase benthic mobility during hypoxic periods, ascending to more oxygenated layers within the water column. *Carcinus maenas*, whilst relatively tolerant of hypoxia, markedly reduces feeding and activity levels under prolonged low-oxygen conditions.

4.3. Feeding Behaviour

All three species under investigation exhibit omnivorous feeding tendencies, yet display pronounced differences with respect to prey selection and hunting technique. *Callinectes sapidus* is an aggressive predator that employs its powerful chelipeds effectively for opening bivalves and extracting polychaetes from sediment (Lipcius et al., 2007; Selfati et al., 2025). *Carcinus aestuarii* pursues prey more actively at night under lagoon conditions, sheltering beneath sediment or large stones during daylight hours. *Carcinus maenas* maintains an exceptionally varied diet; gut content analyses have revealed the consumption of bivalves, gastropods, polychaetes, and crustaceans (Le Calvez, 1987; Elner, 1981).

4.4. Migration and Habitat Utilisation

Callinectes sapidus exhibits dramatic habitat changes throughout its life cycle. Prior to reproduction, females migrate to high-salinity offshore waters, releasing larvae under the high-salinity conditions of the open sea; juvenile individuals subsequently return to low-salinity lagoon interiors to complete their development (Epifanio, 2019). Studies of *Carcinus aestuarii* in the Çardak Lagoon have revealed large seasonal fluctuations in population CPUE values (Acar and Ateş, 2020). *Carcinus maenas* is capable of undertaking vertical habitat shifts on a daily scale in accordance with tidal cycles, and its activity level declines markedly during cold periods (Young and Elliott, 2019).

4.5. Reproductive Behaviour

Reproductive behaviour represents one of the processes in which adaptive strategies linked to environmental conditions are most clearly manifested. In *Callinectes sapidus*, sexual maturity coincides with a single mating event in females, with mature females releasing egg masses into the open sea (Epifanio, 2019). The reproductive period of *Carcinus aestuarii* is concentrated during spring and summer months (Can, 2003). In *Carcinus maenas*, reproduction requires temperate thermal conditions, and reproductive success declines markedly in tropical and very cold water masses (Young and Elliott, 2019).

4.6. Defensive and Avoidance Behaviours

In all three species, moulting (ecdysis) periods represent the most vulnerable phases. During this time, crabs minimise their visibility by sheltering beneath rocks, within sediment, or under dense macroalgal cover. *Callinectes sapidus*, as a proficient swimmer, is capable of performing rapid escape manoeuvres upon perceiving a threat, and shifts to nocturnal activity during periods of high predation pressure. *Carcinus aestuarii* and *C. maenas* both exhibit active escape behaviour as well as defensive posturing, directing their chelipeds towards the source of threat.

5. INTER-SPECIES COMPARISON

5.1. Comparison of Ecological Tolerance Ranges

Table 1 provides a comparative summary of the principal ecological characteristics and tolerance parameters of the three species under investigation.

Feature	<i>C. sapidus</i>	<i>C. aestuarii</i>	<i>C. maenas</i>
Origin	W. Atlantic (invasive)	Mediterranean (native)	E. Atlantic (invasive)
Temperature tolerance	5–35°C	8–34°C	0–33°C
Salinity tolerance	0–35 psu	5–40 psu	4–52 psu
Preferred habitat	Estuary, lagoon, mangrove	Lagoon, shallow coastal	Bay, estuary, harbour
Feeding type	Benthic omnivore	Benthic predator	Aggressive omnivore
Max. carapace width	~230 mm	~60 mm	~95 mm
Status in Türkiye	Invasive, expanding	Native, widespread	Limited records
Invasion risk	High	Low (native)	Moderate–High

Table 1. Comparative summary of the principal ecological characteristics of the crab species investigated.

5.2. Ecological Impacts of Invasive Species

Callinectes sapidus and *Carcinus maenas* are invasive species that exert serious pressure upon native benthic fauna in the ecosystems they colonise. *C. maenas*, in particular, has been documented to cause dramatic declines in bivalve communities in areas it has invaded; it has been identified as a determining factor in the collapse of soft-shell clam (*Mya arenaria*) stocks along the eastern coast

of North America (Glude, 1955). Although the potential impacts of *C. sapidus* on sand clam (*Ruditapes* spp.) and other bivalves in Turkish lagoons have yet to be sufficiently investigated, increasing catch quantities indicate that predation pressure is progressively intensifying.

By contrast, *Carcinus aestuarii*, as a species endemic to the Mediterranean, has occupied an established ecological niche within the lagoon and coastal ecosystems of this sea over the course of evolutionary time, maintaining deeply-rooted ecological relationships with the local biota. Accordingly, its adverse effects upon native species are far more limited compared to invasive species.

5.3. Comparative Assessment from the Perspective of Lagoon Ecosystems

It is evident that all three species fulfil critical functions within lagoon ecosystems. *Carcinus aestuarii*, as the historical predator of Mediterranean lagoons, maintains its position within the food web in a manner compatible with native faunal components. The invasive *C. sapidus* and *C. maenas* carry the potential to disrupt existing trophic structures, and may generate economic losses particularly through their predation pressure on commercially important bivalve species. In the context of Turkish lagoons specifically, *C. sapidus* has displayed an increasingly prominent presence in lagoon systems over the past decade, adopting an opportunistic and expansive strategy.

6. CONCLUSIONS AND RECOMMENDATIONS

Lagoon ecosystems are wetlands of high biological productivity that form transitional zones between marine and terrestrial environments and are highly sensitive to environmental change. The three crab species addressed in this chapter — *Callinectes sapidus*, *Carcinus aestuarii*, and *Carcinus maenas* — respond to the variable conditions offered by lagoon environments through distinct yet complementary adaptation strategies.

All three species exhibit euryhaline and eurythermal characteristics; however, they diverge from one another with respect to temperature and salinity tolerance ranges, migration patterns, feeding strategies, and reproductive timing. The broad ecological plasticity and invasive nature of *Callinectes sapidus* indicate that it has become an increasingly significant pressuring factor in Turkish lagoons. *Carcinus aestuarii*, as a native species, plays a key role in maintaining the ecological balance of Mediterranean lagoon ecosystems. *Carcinus maenas*, although currently displaying limited distribution along Turkish coasts, retains its status as a species requiring close monitoring owing to its invasive potential.

For the sustainable management of lagoon ecosystems, the distribution and population density of invasive crab species must be regularly monitored through long-term surveillance programmes. Fisheries management plans supportive of species life cycles should be developed with due consideration of reproductive periods and habitat utilisation, and biological diversity-focused monitoring

programmes in Ramsar-designated areas should be expanded to include crab species.

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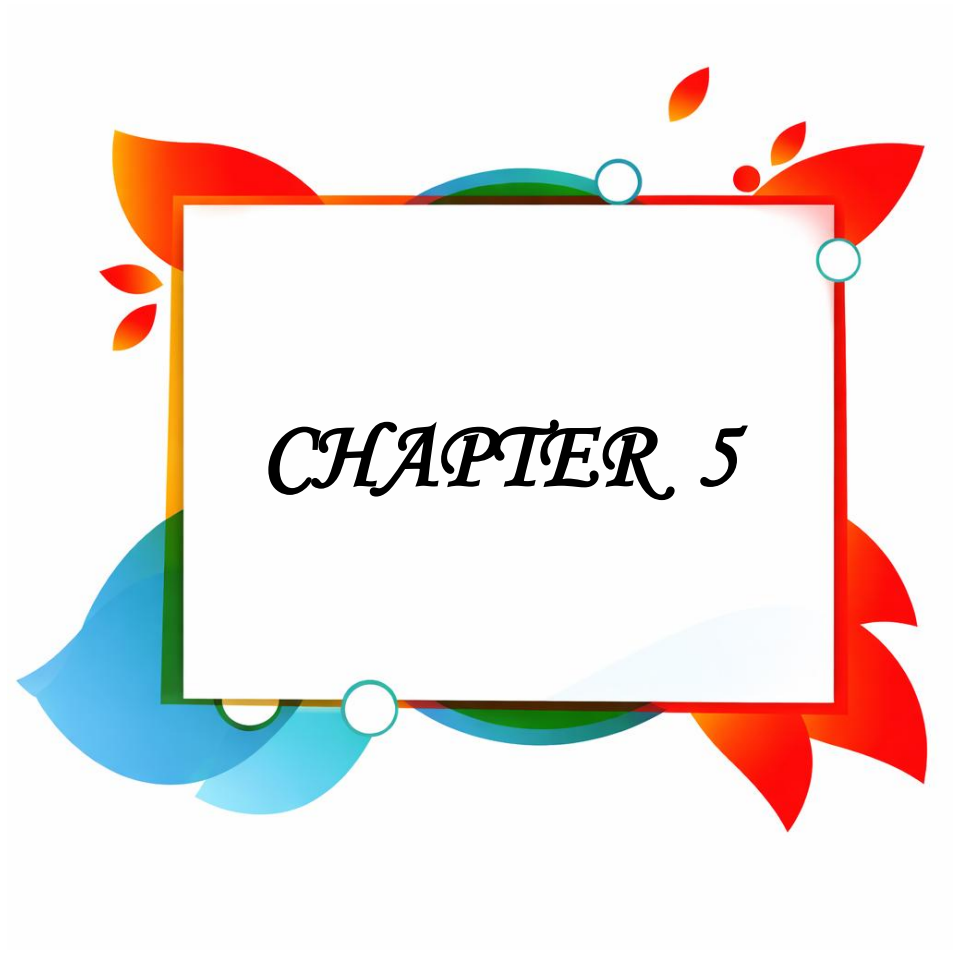
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Drought and Architecture of Plant Survival

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1. Giriş

Drought stress is considered one of the most important abiotic stress factors limiting agricultural production worldwide. Climate change, increasing temperatures, and irregular precipitation patterns adversely affect plant growth and development, leading to significant yield losses. Under conditions of water deficiency, plants attempt to survive by developing various defense mechanisms at morphological, physiological, biochemical, and molecular levels. Drought stress directly affects essential metabolic processes such as photosynthesis, respiration, mineral uptake, and protein synthesis, thereby restricting plant growth and development. In addition, excessive production of reactive oxygen species causes oxidative damage and threatens cellular integrity. Plants attempt to mitigate these adverse effects through antioxidant defense systems, osmotic regulation mechanisms, and the synthesis of stress proteins. Understanding drought tolerance mechanisms is of great importance for sustainable agricultural production. In particular, the development of drought-tolerant plant varieties is considered an effective strategy against future water scarcity. In this review, the effects of drought stress on plants and the adaptation mechanisms developed by plants will be discussed.

2. Drought Stress in Plants and Its Effects

Drought stress occurs when the water requirement of a plant cannot be adequately met (e.g., due to low precipitation or insufficient irrigation), resulting in adverse effects on normal physiological functions such as growth, photosynthetic rate, and stomatal conductance (Anjum et al., 2011). In other words, drought stress arises when water loss from plant leaves exceeds the amount of water absorbed by the roots. This imbalance between water uptake and water loss occurs under conditions where the soil water potential is lower than the root water potential, preventing turgor pressure from maintaining normal physiological functions (Lisar et al., 2012).

According to water availability, drought stress can be classified into two categories: water deficit and dehydration (drying). Water deficit is characterized by restrictions in gas exchange due to stomatal closure in plants experiencing mild water loss with a relative water content (RWC) of approximately 70%,

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whereas dehydration may lead to disruption of cellular structures and enzymatic reactions, cessation of photosynthesis, metabolic disorders, and ultimately plant death (Kage et al., 2004).

Drought stress reduces water potential and turgor pressure in plant cells, thereby increasing the concentration of solutes in the cytosol and extracellular matrix. This condition slows cell growth, resulting in growth inhibition and reproductive failure. Consequently, the accumulation of adaptive osmolytes such as abscisic acid (ABA) and proline is observed. At this stage, excessive production of reactive oxygen species (ROS) further intensifies drought-induced damage in plants. Drought stress not only disrupts water relations in plants but also reduces water content, turgor, and total water amount, causing stomatal closure, restricted gas exchange, reduced transpiration, inhibition of carbon assimilation (photosynthesis), and impaired nutrient-mineral uptake and transport (Reddy et al., 2004).

Another important consequence of drought stress in plants is the synthesis of specific proteins and mRNAs. Under drought conditions, cell expansion slows down or ceases, leading to reduced plant growth. However, drought stress affects cell expansion more severely than cell division. Plant development under drought conditions is significantly influenced by alterations in photosynthesis, respiration, translocation, ion uptake, carbohydrate metabolism, nutrient metabolism, and hormonal balance (Siddiqui et al., 2015).

2.1. Morphological, Anatomical, and Cellular Changes

In most plant species, water stress is associated with changes in leaf anatomy and cellular structure. These changes include a reduction in leaf surface area, decreased stomatal number, thickening of leaf cell walls, cutinization of leaf surfaces, poor development of the vascular system, increased number of large veins, deeper embedding of stomata in succulent and xerophytic plants, tube leaf formation in cereals, and promotion of early senescence as morphological adaptations (Rahman & Hasegawa, 2012). Another study reported that under non-water-restricted conditions, stomatal density was higher than under drought conditions with water limitation; this was attributed to the denser arrangement of stomata on the epidermis due to the narrowing of flag leaf area under stress conditions (Bahar, 2004).

Under drought stress, plants reduce leaf growth, total leaf area, and leaf number to conserve water and improve their adaptation capacity to environmental changes. Drought stress decreases total leaf area and consequently slows photosynthesis. In addition, plants develop a thin waxy layer called the cuticle on leaf surfaces, and leaves become densely covered with hairs. The presence of the cuticle and hairs protects plants from the harmful effects of sunlight while controlling water loss by reducing transpiration. Transpiration is the process by which water evaporates from leaves and other tissues into the atmosphere and is critically important for maintaining water balance in plants. Under drought stress, photosynthetic inhibition occurs through two mechanisms: stomatal control of

photosynthesis and non-stomatal factors controlling photosynthesis (Özcan, 2020).

Water loss in cells disrupts osmotic balance, affecting the functionality of intracellular structures. Along with water loss, deterioration of the cell membrane may occur. The cell membrane consists of a phospholipid bilayer formed by interactions between the hydrophilic heads and hydrophobic tails of phospholipids. When water loss occurs, the decrease in intracellular water levels causes phospholipids to move closer together. Water loss may reduce membrane fluidity, which is an important property determining membrane flexibility and permeability. The membrane becoming more compact may affect the mobility of certain proteins, potentially leading to impaired cellular functions (Aslantaş et al., 2010).

Under drought stress conditions, plant roots extend deeper into the soil to access water resources. The roots of water-stressed plants may become longer relative to the general plant structure. During this process, the plant accelerates its growth stage in an effort to mature earlier (Özer & Sade, 1995).

2.2. Plant Growth and Productivity

A decrease in water potential in plants negatively affects plant growth and productivity, particularly by reducing the rate of cell division due to turgor loss (Kiani et al., 2007). Although different plant organs respond to drought stress at varying degrees, suppression of physiological and biochemical processes in all organs results in reductions in biomolecule concentrations, growth rate, and consequently plant biomass (Esmailpour et al., 2015). Under drought conditions, germination and growth stages are severely affected by inhibition of respiration, ATP production, and electron transport. Plant growth is the result of increases in volume, size, or weight achieved through the maintenance of functional balance between root and shoot systems, meristematic cell division, cell elongation, and differentiation processes. Due to reduced turgor pressure, cell growth is among the physiological processes most sensitive to drought conditions. Under severe drought conditions, cell elongation in higher plants may cease because of interrupted water flow from the xylem to elongating cells (Nonami, 1998). By disrupting mitosis and inhibiting cell elongation and expansion, drought reduces plant growth and yield characteristics (Hussain et al., 2019).

2.3. Nutrient Uptake and Mineral Metabolism

Inorganic nutrient elements such as nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) are critically important for plant growth and biomass production (Ashraf, 2004). Plants require water for nutrient and mineral uptake, dissolution, and mobility. Drought stress reduces soil water availability, decreases nutrient diffusion rates, and inhibits nutrient uptake by plants. Calcium, in particular, is important for maintaining cell membrane integrity, and under drought stress a reduction in Ca^{+2} content occurs; for example, decreases of up to 50% have been observed in the leaves of maize seedlings, while higher levels remain in roots (Nayyar & Walia, 2003). Potassium is essential for water balance,

stomatal movement, and drought resistance, and K^+ deficiency reduces resistance to drought stress (McWilliams, 2003). Disturbances in nitrogen metabolism also negatively affect plant performance by reducing nitrate uptake and nitrate reductase activity (Ashraf & Iram, 2005).

2.4. Photosynthesis and Drought Stress

Drought stress is characterized by reduced water content, decreased leaf water potential, and turgor loss in plants. These conditions lead to stomatal closure and reduced cell growth. Severe water stress may cause cessation of photosynthesis, metabolic disorders, and ultimately plant death (Jaleel et al., 2008). Plants tend to keep their stomata closed in order to minimize water loss; however, this restricts gas exchange and reduces photosynthetic efficiency (Flexas et al., 2004). Photosynthesis is the sole source for the synthesis of sugars necessary for plant growth and development (Chaves et al., 2009). Under drought conditions, the production of reactive oxygen species (ROS), such as superoxide and hydroxyl radicals, may damage the photosynthetic structure (Kuru, 2017).

Rubisco, which plays an important role in carbon metabolism in leaves, functions as a carboxylase in the Calvin cycle and as an oxygenase in photorespiration. Studies have shown that reductions in ribulose-1,5-bisphosphate (RuBP) and Rubisco protein levels during drought stress decrease enzyme activity, thereby inhibiting photosynthetic CO_2 assimilation and causing reductions in plant growth and yield (Flexas & Medrano, 2002). In addition, drought stress negatively affects both cyclic and non-cyclic electron transport processes during photosynthesis. Reduced electron transport rates adversely affect photophosphorylation, decreasing ATP synthesis and $NADP^+$ reduction. Water deficiency also causes ATPase inhibition, leading to reduced ATP levels in chloroplasts. All these factors negatively influence the intensity of photoassimilation and the stability of the photosynthetic system under water stress (Büyük et al., 2012).

2.5. Protein Synthesis

Drought conditions cause both quantitative and qualitative changes in plant proteins. In general, protein levels decrease significantly during drought, mainly due to suppressed synthesis. Drought stress affects gene expression, altering the synthesis of proteins and mRNAs. In response to this stress, plants synthesize mainly dehydrins, proteases, enzymes involved in the biosynthesis of various osmoprotectants, and detoxification enzymes such as SOD, CAT, APX, POD, and GR. In addition, protein factors involved in signal transduction and regulation of gene expression, such as protein kinases and transcription factors, are also produced. Most of these stress-response proteins are dehydrin-like proteins that accumulate in drought-stressed seedlings and during seed production and embryo maturation in many higher plants. These proteins possess highly conserved domains that provide hydrophobic interactions necessary for macromolecular stabilization (Bray, 1993).

2.6. Respiration

Respiration is another important physiological process affected by severe water deficiency, negatively influencing plant growth and yield. Under drought stress conditions, factors such as reduced leaf expansion, deterioration of photosynthetic mechanisms, early leaf senescence, alterations in protein structures, and oxidation of chloroplast pigments and lipids significantly restrict gas exchange parameters in plants. These processes intensify the negative effects of water stress on plant health and adversely affect overall growth and development (Muhammad et al., 2023).

In addition to photosynthesis, gas exchange processes continuously carried out by all plant organs support respiration activities necessary for plant growth and survival. The amount of carbohydrates lost through respiration is an important factor determining the overall metabolic efficiency of the plant. Respiration rate is generally regulated depending on the respiratory substrates used. Under stress conditions, decreases in ATP, NADH, and components of the Krebs cycle reduce respiration rates in plants, negatively affecting their growth and survival abilities (Millar et al., 2010).

2.7. Oxidative Effects of Drought Stress

Oxidative stress in plants involves the presence of excessive amounts of reactive oxygen species (ROS) produced under various environmental stress conditions. These species include singlet oxygen ($^1\text{O}_2$), superoxide radical ($\text{O}_2^{\bullet-}$), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($\text{OH}^\bullet$). Reactive oxygen species interact with macromolecules such as membranes, proteins, lipids, carbohydrates, and nucleic acids, adversely affecting cellular metabolism and causing cellular damage under drought stress conditions (Smirnoff, 1993).

Drought negatively affects photosynthesis in leaves by creating an imbalance between light absorption and utilization. This also leads to a mismatch between electron production and consumption. Excessive accumulation of light energy in the photosynthetic system results in the formation of reactive oxygen species (ROS). ROS production may cause denaturation of functional and structural macromolecules in cells, resulting in harmful effects such as DNA degradation, oxidation of amino acids, proteins, and photosynthetic pigments, as well as lipid peroxidation. Increased ROS production under stress causes lipid peroxidation, protein oxidation, nucleic acid damage, and enzyme inhibition (Yanik et al., 2018).

Under conditions of limited water availability, the primary source of oxidative stress in vegetative plant tissues is thought to be light-chlorophyll interactions occurring in chloroplasts (Farrant, 2000). When water is limited, plants generally close their stomata to prevent water loss, restricting carbon dioxide (CO_2) uptake required for photosynthesis and reducing light-use efficiency. As a result, the amount of NADP^+ , the electron acceptor in photosynthesis, decreases, and ferredoxin reduces oxygen instead of NADP^+ . This leads to the production of

reactive superoxide radicals ($O_2^{\bullet-}$) through electron transfer to oxygen in PSI (Mehler reaction).

The resulting reactive oxygen species may cause oxidative stress by interacting directly or indirectly with cellular macromolecules (Mehler, 1951; Mittler, 2002). In many plant species, the increased production rate of superoxide ($O_2^{\bullet-}$) under drought stress may lead to lipid peroxidation and fatty acid saturation, damaging membrane integrity (Sgherri et al., 1996).

3. Drought Resistance Mechanisms

Plants exhibit various physiological, biochemical, anatomical, and morphological changes to adapt to drought conditions. Plant responses to drought are highly complex processes involving both harmful and adaptive changes. This complexity arises from numerous factors, including plant species and diversity, soil water consumption dynamics, duration and severity of water deficiency, variations in atmospheric water demand, environmental conditions, and the developmental stage of the plant.

In arid regions, terrestrial plants have developed various strategies to withstand severe water stress. In angiosperms, the most common way to avoid water deficiency is through control of germination timing. For example, cacti possess tissue modifications for water storage, whereas roots of Eucalyptus species can penetrate deep into the soil to access available water resources. These examples illustrate strategies to prevent water loss involving modifications in vegetative organs such as leaves and stems (Sgherri et al., 2002).

Under drought conditions, plants optimize the morphology, physiology, and metabolism of their organs and cells to improve productivity. Responses to water stress vary considerably at different organizational levels depending on stress intensity, duration, plant species, and developmental stage. Plants implement specific morphological and physiological changes to minimize stress-induced losses, and significant flexibility exists among and within species.

Reduced biomass, a common phenomenon under drought, varies because different plant organs are affected differently (Shen et al., 2012).

Plant stress resistance can generally be divided into two main groups: stress tolerance and stress avoidance. Drought avoidance is the ability of a plant to maintain high water status or cellular hydration under drought conditions (Blum, 2005). This mechanism occurs either through increased water uptake from the soil or through reduced transpiration (Blum, 2005). Drought avoidance is generally achieved through morphological changes such as reduced stomatal conductance, smaller leaf area, development of extensive root systems, and increased root/shoot ratios (Lei et al., 2006). Increased stomatal and cuticular resistance, smaller stomata, reduced leaf area, and leaf rolling are important drought avoidance strategies that minimize transpiration under stress conditions (Sinclair & Muchow, 2001; Wang & Yamauchi, 2006; Sağlam et al., 2014). However, although reduced leaf area and plant height provide advantages for

limited water use, they may also decrease crop productivity (Sinclair & Muchow, 2001).

On the other hand, drought tolerance is a state of stability achieved through tissue-specific physiological, biochemical, and molecular mechanisms that enable plants to maintain normal functions even at low tissue water potentials. Drought-tolerant plants undergo significant changes in water relations, biochemical and physiological processes, membrane structure, and the structure of subcellular organelles during dehydration. These plants adopt strategies such as stomatal closure, partial senescence of tissues, reduced leaf growth, development of water storage organs, and increased root length and density to use water more efficiently (Özer & Sade, 1995).

Early responses of plants to drought stress generally help prolong survival. Plant adaptation to drought is associated with the accumulation of new metabolites that improve functioning under drought conditions. Plants can tolerate severe dehydration through certain physiological activities such as osmotic adjustment (Luo, 2010). Fundamental aspects of drought responses include maintenance of homeostasis (ionic balance and osmotic adjustment), antioxidant defense systems, and dynamic changes in phytohormones (Verslues et al., 2006).

3.1. Osmotic Adjustment

Water scarcity in arid environments negatively affects plant growth and productivity by reducing tissue water status and turgor (Kiani et al., 2007). Under these conditions, plants attempt to minimize the harmful effects of drought at the cellular level by accumulating organic and inorganic solutes through a mechanism called osmotic adjustment or osmoregulation (Blum, 2005). Osmotic adjustment helps maintain leaf turgor and increases stomatal conductance, thereby supporting efficient CO₂ uptake (Kiani et al., 2007) and enhancing the water uptake capacity of roots (Chimenti et al., 2002). Osmoprotectants, which are low molecular weight solutes, help maintain turgor pressure by regulating homeostasis while also protecting cellular enzymes and macromolecules from damage caused by reactive oxygen species (ROS). Under drought conditions, the accumulation of compatible solutes such as free proline, free amino acids, and glycine betaine constitutes one of the physiological responses of plants (Farooq et al., 2009).

Proline is an important compatible solute, particularly in young leaves of water-stressed plants. Its presence at high levels enables plants to maintain low water potentials. In addition to osmoregulation, this amino acid can also be considered a protective compound against osmotic stress (Sankar et al., 2008). Proline plays a critical role in maintaining cellular osmotic potential and protecting against severe dehydration. High proline levels enhance the ability to cope with the negative effects of drought and reduce ROS-induced cellular damage; therefore, elevated proline content is directly associated with drought tolerance in plants (Anjum et al., 2011).

Compared to other amino acids, proline accumulates at higher concentrations under water deficit conditions (Zhang et al., 2009) and plays an important role in buffering cellular redox potential (Kaur & Asthir, 2015). In addition to its function in osmoregulation, glycine betaine (GB) has been shown to protect functional proteins, enzymes, and lipids involved in photosynthesis and to maintain electron flow in thylakoid membranes (Xing & Rajashekar, 1999). Therefore, osmotic adjustment achieved through the accumulation of various organic and inorganic solutes, together with increased activity of antioxidant enzymes in leaves, is considered one of the essential physiological adaptations of drought-sensitive plants (Lei et al., 2006). These adaptations enable plants to become more resistant to drought conditions while minimizing damage during the process. Furthermore, many studies have demonstrated a relationship between osmotic adjustment and plant growth and yield (Guóth et al., 2010).

3.2. Antioxidant Defense System

Under drought conditions, limited water availability promotes excessive production of reactive oxygen species (ROS), thereby increasing oxidative stress. This situation leads to reduced CO₂ flow due to stomatal closure and consequently decreases enzyme activity and photosynthetic efficiency. As a result, various ROS such as O^{2•-}, H₂O₂, OH[•], and ¹O₂ are generated (Lawlor & Cornic, 2002). To minimize the harmful effects caused by oxidative stress and sustain metabolic activities, plants activate both enzymatic and non-enzymatic defense mechanisms (Horvath et al., 2007). Enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione reductase (GR), and ascorbate peroxidase (APX), whereas non-enzymatic antioxidants include ascorbic acid, α-tocopherol, reduced glutathione, β-carotene, polyamines, salicylates, proline, and compatible solutes such as glycine betaine (GB). These compounds increase their production under drought stress to protect plants against oxidative damage (Scandalios, 2005).

The balance between ROS production and antioxidant enzyme activities determines the development of oxidative signaling and whether damage will occur (Møller et al., 2007). Non-enzymatic antioxidants work cooperatively to maintain the integrity of photosynthetic membranes under oxidative stress. Enzymatic components function either by directly scavenging ROS or by producing non-enzymatic antioxidants. Efficient elimination of O^{2•-} and H₂O₂ in plant cells requires the coordinated action of antioxidants. O^{2•-} can be converted into H₂O₂ by SOD in chloroplasts, mitochondria, cytoplasm, and peroxisomes. Subsequently, POD plays a critical role in scavenging H₂O₂ generated through SOD-catalyzed dismutation of O^{2•-}. Catalase (CAT) is the primary enzyme responsible for eliminating H₂O₂ in mitochondria and microbodies (Shigeoka et al., 2002), thereby helping to reduce the harmful effects of oxidative stress. CAT located in peroxisomes is considered an indispensable component in the decomposition of H₂O₂ under stress conditions.

Maintaining antioxidant enzyme activities at high levels can increase plant resistance to oxidative damage and alleviate the effects of drought stress (Sharma

& Dubey, 2005). The potential of these enzymes to effectively scavenge reactive oxygen species and consequently reduce their harmful effects is regarded as an important indicator of plant resistance to drought conditions.

In particular, antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase regulate cellular homeostasis by controlling excessive ROS accumulation in plant cells. The activity levels of these enzymes are associated with drought stress intensity; high enzyme levels support better plant performance under stress conditions. For example, during drought conditions, enhanced activities of these enzymes help protect photosynthetic mechanisms and overall metabolism against stress factors such as cellular water loss and turgor reduction. This not only ensures the continuity of intracellular biological processes but also enhances plant adaptation capacity to drought. Thus, the functionality of antioxidant enzymes becomes one of the key elements reinforcing plant tolerance to environmental stress conditions (Kireççi, 2018).

4. Physiological Changes

4.1. Reduction in Transpiration

Under water stress conditions, plant stomata tend to close, leading to a decrease in transpiration rate. Mechanisms contributing to stomatal closure under water stress include accumulation of the hormone abscisic acid (ABA), potassium (K) ion levels, and factors related to the turgor pressure of guard cells. In water-stressed plants, ABA concentration in stomatal cells increases, resulting in the accumulation of water-insoluble starch and a reduction in potassium ions. While some genes respond rapidly to drought stress, others are induced more slowly following ABA accumulation. Consequently, stomatal cells with reduced osmotic pressure lose turgor pressure and undergo closure (Kalefetoğlu, 2005).

4.2. Osmotic Regulation

Plants subjected to water stress attempt to balance their osmotic potential by accumulating certain organic solutes in order to maintain cellular turgor. In this process, the increase in soluble carbohydrates plays an important role. These substances include sugars (such as glucose and sucrose), amino acids (such as proline), malate, and other low molecular weight compounds. The accumulation of these compounds increases cellular osmotic pressure, allowing cells to retain more water. Osmotic regulation formed in response to drought stress is achieved through specific enzymes involved in osmolyte synthesis, such as proline-5-carboxylate synthetase, proline-5-carboxylate reductase, betaine aldehyde dehydrogenase, and choline monooxygenase (Kalefetoğlu, 2005).

4.3. Reduction in Photosynthesis

Water stress significantly limits the energy production potential of plants by directly affecting photosynthesis processes (through stomatal closure and chloroplast functionality) and indirectly affecting them through metabolic changes and oxidative stress. In photosynthesis, chloroplasts function as organelles that convert light energy into chemical energy within plant cells.

Photosynthesis is a biochemical process involving light-dependent reactions and light-independent reactions (Calvin cycle). Enzymes playing critical roles in these processes support ATP and NADPH production and convert carbon dioxide into organic molecules. For example, the enzyme ribulose biphosphate carboxylase/oxygenase (RuBisCO) catalyzes the carboxylation of ribulose biphosphate with carbon dioxide. Reduced enzyme activity decreases the efficiency of carbon fixation and consequently limits the synthesis of organic compounds. Declines in the activity of these biochemical components within chloroplasts also affect the photosynthetic capacity and overall metabolic efficiency of the plant (Kutlu, 2010).

4.4. Stomatal Limitation

The two main factors causing stomatal closure during drought are hydraulic signals (leaf water potential and cell turgor) and chemical signals (abscisic acid) (Kalefetoğlu, 2005). During periods of water deficiency, stomata close as a result of turgor loss in guard cells, thereby reducing evaporation (Öztürk & Akten, 1996). Since stomata are structures located on the lower and upper epidermis of leaves that regulate gas exchange (carbon dioxide and oxygen) and water evaporation, their opening and closing are critically important for plant survival. Guard cells possess a mechanism controlling the entry of water and ions. This mechanism is regulated through stomatal turgor pressure and hormonal control.

- **Turgor Pressure:** Expansion of guard cells through water uptake enables stomatal opening. When water loss occurs, the reduction in intracellular water causes specialized cells to shrink, leading to stomatal closure.

- **Hormonal Control:** In plants exposed to drought stress, ABA levels increase in stomatal cells, resulting in the formation of water-insoluble starch and a decrease in K ions (Kutlu, 2010).

Water limitation also determines stomatal density in plants. Indeed, in a study conducted under water-limited (rainfed) and non-water-limited (irrigated) conditions in bread and durum wheats, the number of stomata (as a total of lower epidermis and upper epidermis) on the flag leaf was found to be higher in durum wheats than in bread wheats. The same study also reported that both wheat species exhibited higher stomatal density under rainfed conditions compared to irrigated conditions, as an indicator of adaptation (Bahar, 2011).

5. Molecular-Level Effects of Drought Stress

Water stress promotes the accumulation of reactive oxygen species (ROS), thereby increasing oxidative stress levels. This increase in ROS ultimately leads to cell injury through damage to cell membranes, deterioration in the structure and function of intracellular proteins, and structural damage to DNA (Özcan et al., 2015). Peroxidation occurring in biological membranes causes disruption of membrane fluidity, reduction in membrane potential, and increased membrane permeability to H^+ and other ions, resulting in membrane deterioration and release of organelle contents into the cytoplasm (Özcan et al., 2015). When intracellular protein structures are exposed to oxidation processes, carbonyl

groups are formed in side chains such as proline, arginine, lysine, and threonine. Protein carbonyl compounds may also arise through α -amidation pathways and oxidation of glutamyl side chains as a result of protein degradation. Additionally, cysteine, histidine, and lysine residues on protein side chains may form carbonyl groups through secondary reactions involving aldehydes produced during lipid peroxidation (e.g., malondialdehyde [MDA] and 4-hydroxynonenal [HNE]), carbonyl compounds formed by reducing sugars (ketoamines and ketoaldehydes), and oxidation products of lysine residues in proteins (glycation and glycoxidation).

As a result, cell damage or cell death may occur. Plants have developed various adaptive mechanisms against oxidative stress. Among these mechanisms, antioxidant defense systems aimed at balancing reactive oxygen species are particularly important. Plants synthesize various enzymes such as abscisic acid (ABA), superoxide dismutase (SOD), glutathione peroxidase, and catalase to regulate ROS levels. Genotypes with high ABA assimilation exhibit better water use efficiency and lower stomatal permeability (Öztürk & Akten, 1996).

These enzymes play important roles in converting reactive oxygen species into less reactive forms. ROS can interact with DNA, damaging its structural integrity and leading to genetic mutations. Increased RNase enzyme activity under drought stress causes nucleic acid degradation and destroys messenger RNA that binds ribosomes, thereby reducing polyribosome content (Kutlu, 2010).

5.1. Non-Enzymatic Antioxidants

5.1.1. Ascorbic Acid (Vitamin C)

Ascorbic acid neutralizes the harmful effects of free radicals and reactive oxygen species in plants, preventing cellular damage and helping plants cope with oxidative stress. It also plays a role in the synthesis of important structural proteins such as collagen and lignin and supports the stabilization of chloroplasts and other cellular organelles. During photosynthesis, particularly in light-dependent reactions, ascorbic acid enhances photosynthetic efficiency by reducing the harmful effects of reactive oxygen species. In this way, it contributes to the effective adaptation of plants to various environmental stress factors (Pavet et al., 2005).

5.1.2. Tocopherols (Vitamin E)

Tocopherols are lipophilic antioxidants in plants that effectively neutralize free radicals and reactive oxygen species. These properties protect cell membranes against oxidative stress and lipid peroxidation, thereby enhancing plant resistance to aging and environmental stress conditions. Furthermore, tocopherols preserve membrane integrity and functionality by preventing oxidative damage to lipids in plant cell membranes. During photosynthesis, they improve photosynthetic efficiency by neutralizing reactive oxygen species formed in chloroplasts (Kavukçu, 2016).

5.1.3. Carotenoids

Carotenoids function as lipophilic antioxidants that effectively neutralize free radicals and reactive oxygen species. Under water stress conditions, these antioxidant properties help reduce cellular oxidative damage and prevent oxidative deterioration of biomolecules such as lipids, proteins, and DNA. By preventing oxidative damage to lipids, carotenoids maintain the structural integrity of cell membranes and thereby support cellular stability (Havaux, 1998). Additionally, under stress conditions, plants activate their defense mechanisms by increasing carotenoid synthesis (Ghanem & El-Farouk, 2024; Çelik, 2025).

5.1.4. Glutathione

Glutathione exists in two main forms: reduced glutathione (GSH) and oxidized glutathione (GSSG). Under water stress, increased oxidative stress within cells causes oxidation of GSH and accumulation of GSSG. In this situation, the enzyme glutathione reductase converts GSSG back into reduced GSH, thereby contributing to the maintenance of cellular redox balance and management of oxidative stress (Foyer & Noctor, 2011).

5.1.5. Phenolic Compounds

Phenolic compounds are known for their high antioxidant capacities. Under water stress conditions, the production of free radicals and reactive oxygen species increases. Phenolic compounds effectively neutralize these reactive oxygen species, thereby reducing cellular oxidative damage. This process plays a protective role, particularly against oxidative damage to cellular components such as lipids, proteins, and DNA. Studies have shown that phenylpropanoid metabolism and phenolic compound levels increase under different environmental factors and stress conditions (Büyük et al., 2012).

5.2. Enzymatic Antioxidants

5.2.1. Superoxide Dismutase (SOD)

SODs are metalloproteins with exceptionally high catalytic activity (Büyük et al., 2012). They are vital antioxidant enzymes involved in managing oxidative damage associated with water stress in plants. This enzyme converts superoxide anion radicals (O_2^-) into oxygen (O_2) and hydrogen peroxide (H_2O_2). Under water stress conditions, free radical production increases in plants, and superoxide radicals play a significant role in this increase. SOD effectively neutralizes these reactive oxygen species and reduces cellular oxidative damage. By converting superoxide radicals into hydrogen peroxide, SOD controls hydrogen peroxide accumulation. Subsequently, hydrogen peroxide is detoxified by other antioxidant enzymes such as catalase and glutathione peroxidase. This process contributes to the maintenance of cellular oxidative balance and effective management of stress responses (Dhanda et al., 2004).

5.2.2. Ascorbate Peroxidase (APX)

Ascorbate peroxidase (APX) catalyzes the reduction of hydrogen peroxide (H_2O_2) into water (H_2O) and dehydroascorbate (DHA) using ascorbate (vitamin C). This mechanism prevents the accumulation of hydrogen peroxide in plant cells and neutralizes its oxidative harmful effects. Under water stress conditions, hydrogen peroxide levels increase, and APX plays an important role in its effective detoxification. The dehydroascorbate produced is reduced back into active ascorbate in the cellular environment, thereby maintaining antioxidant capacity (Şahin & Torun, 2024).

5.2.3. Catalase (CAT)

Catalase plays a critical role as an enzyme converting hydrogen peroxide (H_2O_2) into water (H_2O) and oxygen (O_2). Under water stress conditions, hydrogen peroxide levels increase, which may result in oxidative damage to cellular components. Catalase works together with other antioxidant enzymes such as superoxide dismutase (SOD) and ascorbate peroxidase (APX) to form a comprehensive antioxidant defense mechanism against oxidative stress in plants (Aras et al., 2012). In a study adapting drought and heat tolerance tests developed for sorghum to wheat, Blum and Ebercon evaluated drought tolerance of wheat leaves through electrical conductivity measurements in leaf discs exposed to water stress using a 40% PEG solution. The researchers reported that drought tolerance decreased with plant developmental stage and that the best discrimination was obtained during the late growth stage (Blum & Ebercon, 1981).

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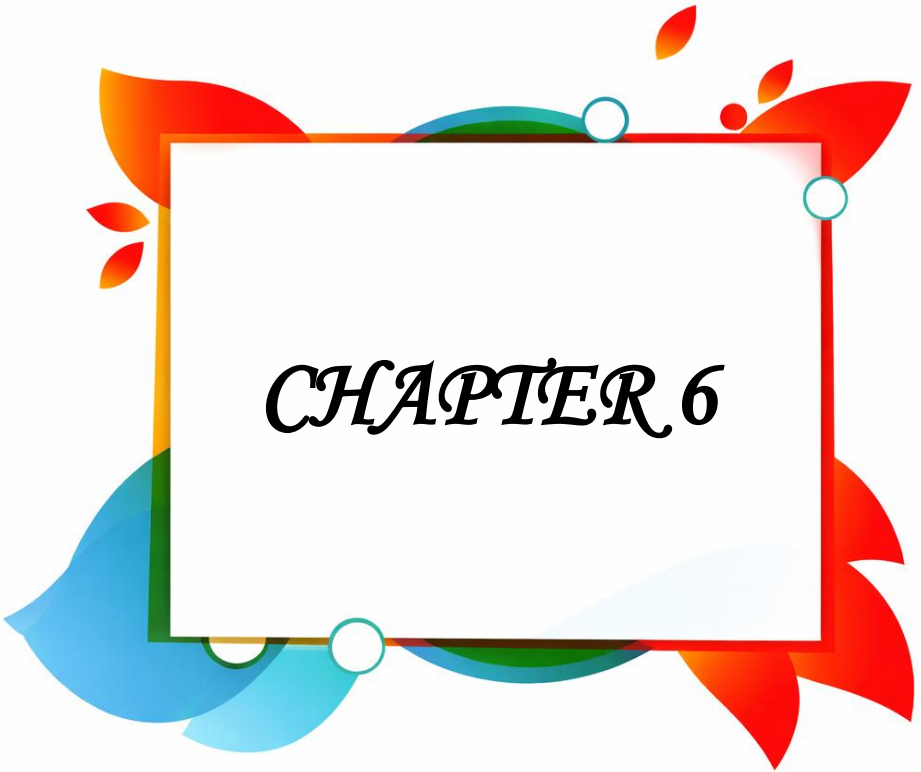
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CHAPTER 6

Modeling Current and Future Agro-Climatic Suitability for Pistachio (*Pistacia vera* L.) Cultivation in Türkiye under Climate Change Scenarios Using MaxEnt

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1.Introduction

Pistachio (*Pistacia vera* L.) (Figure 1a, 1b) belongs to the family Anacardiaceae within the plant kingdom and is classified under the genus *Pistacia* (Ferguson, Polito & Kallsen, 2005). Species of this genus thrive in suitable ecological conditions between the 30°–45° latitudinal parallels in both the northern and southern hemispheres (Tekin et al., 2020). Within the genus *Pistacia*, *Pistacia vera* L. is the most commercially valuable species (Onay et al., 2012). This is because, among *Pistacia* species, only *Pistacia vera* L. is cultivated for its edible nuts (Figure 1c, 1d), while other species are primarily used as rootstocks or for various industrial applications (Mandalari et al., 2021). It is noteworthy that *Pistacia vera* L. occurs in Türkiye both as limited wild or semi-natural populations and, predominantly, as a cultivated tree crop. Although several wild *Pistacia* species naturally occur across the southeastern and Mediterranean regions of the country, commercial pistachio production relies largely on managed orchards established through grafting. In these systems, pistachio scions are grafted onto rootstocks of wild *Pistacia* species, particularly *Pistacia terebinthus* L., *Pistacia khinjuk* Stocks, and *Pistacia atlantica* Desf. (Atlı et al., 2001; İlikçioğlu, 2022). Consequently, the present study does not attempt to model the natural ecological niche or wild biogeographical distribution of the species; rather, it focuses on identifying the agro-climatic envelope that supports successful pistachio cultivation under current and future climate conditions.

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Figure 1. Example pistachio orchard (a; Adıyaman, Türkiye), unprocessed pistachios on the tree (b; Gaziantep, Türkiye), processed pistachio products for consumption (c, d)

Commercial pistachio production is primarily carried out in the USA, Iran, Türkiye, China, and Syria (FAO, 2025). Due to its high commercial value, pistachios are often referred to as "green gold" or the "golden tree" in Türkiye and several Middle Eastern countries (İlikçioğlu, 2022). Pistachio known for its resilience to arid and semi-arid climates and adaptability to diverse soils, has a requirement for long, hot summers and cold winters for optimal fruit development (Onay et al., 2012). Türkiye, one of the world's leading pistachio producers, primarily cultivates pistachios in Şanlıurfa, Gaziantep, Siirt, and Adıyaman in the Southeastern Anatolia Region; Kahramanmaraş and Mersin in the Mediterranean Region; and Manisa, İzmir, and Aydın in the Aegean Region. According to data from the Turkish Statistical Institute (TurkStat), the highest production levels on average between 2004 and 2023 were recorded in Şanlıurfa, Gaziantep and Siirt provinces (TurkStat, 2025).

Climate change refers to statistically significant shifts in the long-term averages of climate elements, resulting from natural processes or human activities (Türkeş, 2019). In its 6th Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) highlights that anthropogenic activities have been the primary driver of rising greenhouse gas concentrations since 1750. The report also states that the global surface temperature during the 2001–2020 period was approximately 1°C higher compared to the 1850–1900 period (IPCC, 2021). According to climate projections, global warming is expected to increase by up to 1.5°C in the low-emission scenario (SSP1-1.9) in the near term (2021–2040), approximately 3°C in the medium-emission scenario (SSP2-4.5), and

approximately 4.5°C in the very high-emission scenario (SSP5-8.5) in the long term (2081–2100) (IPCC, 2023). This rising trend in global temperatures makes climate change an increasingly critical environmental threat, leading to significant challenges across political, economic, social, and ecological dimensions (Özdel, 2020; Droulia & Charalampopoulos, 2021; Tuğaç, 2022; Özdel & Meydan, 2024). Rising temperatures, shifting precipitation patterns, greater seasonal variability, and increasingly frequent and severe weather extremes are profoundly impacting ecosystems and biodiversity as a result of global climate change (Diffenbaugh & Field, 2013). In particular, vulnerable species that struggle to adapt to the abiotic stresses caused by climate change may face significant challenges (Foden et al., 2019). Changing climatic conditions could drive some species to extinction (Cahill et al., 2013), alter the geographical distribution of others (Pech et al., 2017), or lead to shifts in phenology (Türkoğlu, Şensoy & Aydın, 2016).

Species Distribution Models (SDMs) are commonly applied to evaluate how climate change may influence the geographic ranges of species and the climatic suitability of agricultural crops (Miller, 2010; Rathore & Sharma, 2023; Özdel et al., 2025). They play a crucial role in predicting past, present, and future species distributions (Koç, Biltekin & Ustaoglu, 2021; Koç, Dalfes & Avcı, 2022; Hosseini, Ghorbanpour & Mostafavi, 2024). In the literature, commonly used SDM tools include the Generalized Linear Model (GLM), Random Forest (RF), Genetic Algorithm for Rule-set Production (GARP), CLIMEX, BIOCLIM, and the Maximum Entropy Model (MaxEnt) (Huang et al., 2023; Shabani & Kumar, 2014). MaxEnt (Phillips et al., 2017), one of the most widely used methods for predicting species distributions, is a powerful and competitive modeling tool that estimates the potential distribution of species by analyzing their relationships with environmental factors (Elith et al., 2011). This method aims to generate highly accurate and reliable models by maximizing entropy in the relationship between existing species data and environmental variables (Elith et al., 2011; Merow, Smith & Silander, 2013).

Agriculture is an activity highly dependent on climatic conditions. Both short- and long-term changes in climate, along with extreme weather events, significantly impact agricultural production (Reddy, 2015). Climate change alters the phenological stages of plants, affecting their growth and development processes (Gordo & Sanz, 2010), shifting planting and harvesting times (Cook & Wolkovich, 2016), and influencing crop productivity and quality (Rezaei et al., 2023). For instance, rising temperatures can lead to early flowering and ripening (Tun et al., 2021), while increased drought conditions can result in water shortages and various physiological stress responses (Seleiman et al., 2021). Additionally, climate change affects the spread of diseases and pests, posing further risks to agricultural production (Singh et al., 2023). These factors necessitate the reorganization of agricultural practices, including irrigation and

soil management, fertilization, pruning, variety selection, and harvesting. Under increasingly severe climatic conditions, agricultural activities may decline or even disappear in certain regions, leading to shifts in the geographical distribution of agricultural production. As a result, new plantation areas may be established in regions with more favorable climatic conditions. This issue has been widely discussed and evaluated in numerous studies (Zhao et al., 2021; Ali et al., 2023; Gao et al., 2024; Özdel, Ustaoglu & Cürebal, 2024).

Scientific literature extensively demonstrates the impacts of climate change on agricultural productivity, habitat loss in wild plants and shifts in geographical suitability of agricultural crops, emphasizing that these effects are particularly pronounced in species with high sensitivity to specific temperature conditions (Menzel et al., 2006; Luedeling, 2012; Ab Lah et al., 2021; Zhao et al., 2021; IPCC, 2023; Özdel et al., 2024). Studies consistently highlight the vulnerability of economically valuable tree nut species to seasonal changes (An et al., 2020; Djaman et al., 2021; Freitas et al., 2023; Luedeling et al., 2009, 2011). *Pistacia vera* L., whose productivity relies on a delicate balance between cold winter conditions and hot summer periods, is especially susceptible to the risks posed by climate change (Javanshah, 2010; Çelik et al., 2018; Ahmadi & Baaghdeh, 2020; Ahmadi, Baaghdeh & Dadashi-Roudbari, 2021). Climate-induced disruptions of this balance can result in significant declines in yield and product quality (Ahmadi, Baaghdeh & Dadashi-Roudbari, 2021), creating additional socio-economic pressures on farming communities that are particularly vulnerable to climate change in arid regions (Asrari, Omidi & Hosseini, 2023). Moreover, climate change also affects pistachio pest populations, increasing pest pressure and thereby introducing further risks to yield and quality (Pathak, Maskey & Rijal, 2021).

The socio-economic and ecological significance of the tree extends beyond its fruit, as its biomass-including shells and pruning residues-offers bioenergy potential, while plantations contribute valuable ecosystem services by storing substantial amounts of carbon in both biomass and soil (Çelik & Demirer, 2015; Çelik et al., 2017; Taghizadeh-Alisaraei et al., 2017). Despite these climatic, economic, and ecological values, comprehensive assessments modeling the future spatial distribution of *Pistacia vera* L. under climate change scenarios remain largely absent from the literature, particularly in Türkiye, a global production center. This research gap underscores the innovative aspect of the present study.

Türkiye, largely situated in the subtropical macroclimatic zone of the Mediterranean, lies between 36°–42° north latitude and 26°–45° east longitude. The country's climate is shaped by several key factors, including its geographical location, the influence of various air masses, the variability of landforms over short distances, and the interplay between maritime and continental effects

(Koçman, 1993; Yetmen, 2020). These factors not only determine Türkiye's climate but also influence the distribution of plant species and contribute to the diversification of agricultural production patterns. Türkiye is located in the Mediterranean Basin, one of the regions where climate change is most intensely felt (Lazoglou et al., 2024), placing the country among those at high risk in terms of climate change impacts (Türkeş, 2017). Studies indicate a statistically significant increase in both average temperatures and temperature extremes in Türkiye (Kızılelma, Çelik & Karabulut, 2015; Acar Deniz & Gönençgil, 2017; Aykır, Atalay & Coşkun, 2022). Moreover, future climate projections predict a substantial rise in temperatures (Demircan et al., 2017; Hüdaverdi et al., 2016). These changes will inevitably impact the country's agricultural production (Bozoğlu et al., 2019). In particular, pistachio cultivation, which is predominantly concentrated in the southern regions, is believed to be at risk due to the increasing effects of climate change. Accordingly, this study aimed to identify the current and future agro-climatic suitability of pistachio cultivation areas in Türkiye and to assess potential changes under climate change scenarios, focusing on agricultural suitability rather than the natural ecological niche of the species, since pistachio in Türkiye is primarily cultivated rather than naturally distributed. The lack of prior analyses on this species within this context served as the primary motivation for conducting the study. In line with this objective, the study sought to answer the following questions:

1. Which environmental variables most influence the agro-climatic suitability of pistachio cultivation?
2. Based on bioclimatic variables from the period 1970–2000, what is the estimated current cultivation suitability of pistachios in Türkiye?
3. How will the future agro-climatic suitability of pistachio cultivation change under the SSP2-4.5 and SSP5-8.5 scenarios for the periods 2041–2060 and 2081–2100 according to the IPSL-CM6A-LR global circulation model?
4. How do the current and projected future cultivation suitability areas compare spatially?

2. Materials and Methods

2.1. Study Area

The modeling process was initially conducted over a broad area encompassing Türkiye and its surrounding regions (Figure 2a), and MaxEnt models were created based on this extent. Subsequently, the study area was clipped to the national boundaries of Turkey using Geographic Information System (GIS) tools, with large lakes such as Tuz Lake and Van Lake masked. Finally, all calculations were performed over a total study area of 773,563 km². This approach was implemented to ensure that the model outputs are meaningful and comparable at the country scale (Figure 2b).

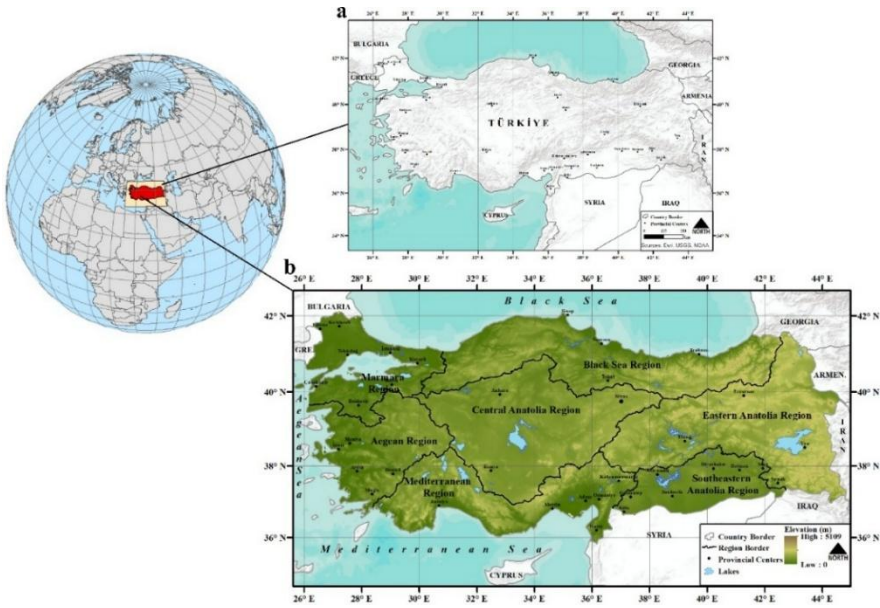


Figure 2. Study area location map. (a) The initial modeling domain, encompassing Türkiye and surrounding regions. (b) The final study area, clipped to the national boundaries of Türkiye, where all final calculations were performed.

2.2. Occurrence Records for Spatiotemporal Analysis

Pistacia vera L., the primary focus of this study, holds a significant place in Türkiye's agricultural production and biodiversity. The species' occurrence data were derived from the Global Biodiversity Information Facility (GBIF, 2025) and GPS records collected from pistachio orchards in areas where pistachio cultivation occurs. Because *Pistacia vera* is largely cultivated rather than naturally distributed in Türkiye, these occurrence points represent cultivation sites rather than wild populations. Therefore, the modeling framework aims to estimate agro-climatic suitability for pistachio cultivation rather than the natural ecological niche of the species.

GBIF is an open-access, freely available database widely used in species distribution and ecological niche modeling studies (Santana et al., 2019; Zhang et al., 2021; Koç, Ustaoglu & Biltekin, 2024). To ensure data accuracy, the occurrence records for Türkiye and its immediate surroundings obtained from GBIF were verified using Google Earth Pro, and erroneous records were removed from the dataset. The occurrence dataset used in this study consists of two complementary components: (i) verified pistachio orchard records representing actual cultivation sites, and (ii) GBIF occurrence records representing the broader ecological and climatic tolerance of the species. Although GBIF records do not exclusively represent cultivated orchards, they provide valuable information on the environmental conditions under which *Pistacia vera* L. can survive. When

combined with verified orchard data, these records help to approximate the agro-climatic envelope within which pistachio cultivation may be feasible.

In total, 114 occurrence records were used in the modelling process. Although the number of records is relatively limited, all points were carefully validated and selected to ensure data reliability and to represent both cultivation conditions and the broader climatic tolerance of the species. However, it should be noted that GBIF records may include non-cultivated occurrences and therefore do not directly reflect agricultural productivity or management conditions. Nevertheless, they provide valuable information on the climatic tolerance limits of the species. Accordingly, the results should be interpreted as an approximation of agro-climatic suitability, offering a useful basis for identifying potentially suitable cultivation zones rather than a direct representation of optimal production areas. Finally, these records were georeferenced using GIS and converted to .csv format for use in analyses.



Figure 3. Spatial distribution of pistachio occurrence data (cultivation records) used in the modelling process (n = 114)

The occurrence dataset used in this study consists of two complementary components: (i) verified pistachio orchard records representing actual cultivation sites, and (ii) GBIF occurrence records representing the broader ecological and climatic tolerance of the species. Although GBIF records do not exclusively represent cultivated orchards, they provide valuable information on the environmental conditions under which *Pistacia vera* can survive. When combined with verified orchard data, these records help to approximate the agro-climatic envelope within which pistachio cultivation may be feasible. However, it should be noted that GBIF records may include non-cultivated occurrences and do not directly reflect agricultural productivity or management conditions. Therefore, the results should be interpreted as an approximation of agro-climatic suitability rather than a direct representation of optimal cultivation zones.

2.3. Bioclimatic and Other Environmental Variables

This study integrates bioclimatic variables with other environmental factors such as elevation, slope, aspect, and soil to assess the current and future cultivation suitability of pistachio cultivation areas both temporally and spatially. Nineteen bioclimatic variables with a spatial resolution of 30 seconds ($\sim 1 \text{ km}^2$), derived from temperature and precipitation data from the open-access WorldClim database (<https://worldclim.org>), were used to identify current and potential future agricultural areas (Figure 4). These bioclimatic variables capture temperature and precipitation patterns, seasonal variations, and extreme or limiting environmental conditions that influence the environmental suitability of species (Örücü et al., 2024). Additionally, topographic and edaphic factors—such as elevation, slope, aspect, and soil—play a crucial role in determining habitat suitability and shaping the ecological niches of species (Dubuis et al., 2013; Wang et al., 2014).

Bioclimatic data corresponding to the 1970–2000 reference period were obtained from the WorldClim database to identify the current potential cultivation suitability areas. The SSP2-4.5 and SSP5-8.5 emission scenarios of the IPSL-CM6A-LR global circulation model were used for the periods 2041–2060 and 2081–2100 to predict the possible future cultivation suitability areas. IPSL-CM6A-LR not only models the physical atmosphere, land, ocean, and sea ice but also incorporates the carbon cycle (Boucher et al., 2020). The two scenarios, SSP2-4.5 and SSP5-8.5, were considered in this study as they are widely used in SDMs to represent intermediate (moderately optimistic) and high-emission (pessimistic) climate futures, allowing the assessment of potential range shifts and changes in habitat suitability for *Pistacia vera* under contrasting climate conditions. Soil data were derived from the FAO Digital Soil Map of the World (DSMW), while elevation, slope, and aspect maps were generated using SRTM elevation data with a 30-second spatial resolution provided by WorldClim 2.1. All estimated variables for the study area were converted to .ascii format for use in the modelling phase.

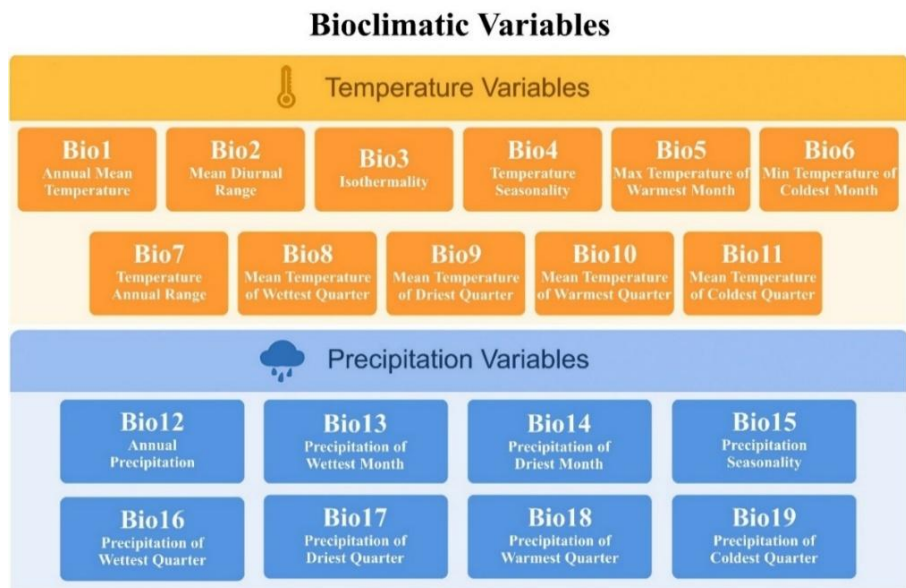


Figure 4. Bioclimatic variables used in the study (Source: <https://www.worldclim.org/data/bioclim.html>)

2.4. Statistical Analyses and Mapping

Before the modelling stage, Pearson correlation analysis was conducted to address potential multicollinearity issues among the variables (Hosseini et al., 2024; Yang et al., 2023). In the resulting correlation matrix, variables with a correlation coefficient of $|r| \geq 0.85$ were excluded from the modelling process to ensure the reliability of the predictions (Dagtekin et al., 2020; Koç et al., 2021).

MaxEnt 3.4.4 software, which applies the Maximum Entropy principle based on machine learning, was used to determine both the current potential and future agricultural areas suitable for pistachio cultivation. MaxEnt provides several advantages, including ease of use, the ability to generate high-performance models with incomplete data, and the capability to work solely with occurrence data (Phillips, Anderson & Schapire, 2006; Phillips et al., 2017). Because of these benefits, it is often employed in modeling species distributions and ecological niches (Elith et al., 2011; Merow et al., 2013; Purohit & Rawat, 2022). In the MaxEnt software, fitness estimates were obtained using the Cloglog transformation, and models were generated with the Auto features option (Phillips et al., 2017). To evaluate the reliability and accuracy of the model, a cross-validation approach was implemented (Hijmans, 2012). To ensure reliable predictions, the modeling process was repeated 10 times using 10,000 background points, and the final results were derived by averaging these repetitions (Zhao et al., 2022). Additionally, the Jackknife test was applied to assess each variable's contribution and influence in the modeling process. This

test identifies the most influential variables by analyzing each variable's independent impact on the model (Remya, Ramachandran & Jayakumar, 2015).

The performance of the models developed with MaxEnt software was evaluated using the Area Under the Curve (AUC) value, determined through Receiver Operating Characteristic (ROC) analysis (Phillips et al., 2006). AUC is a widely used performance metric that indicates the model's ability to distinguish between occurrence records and randomly selected background points. The AUC value ranges from 0 to 1, with higher values reflecting improved model performance (Phillips et al., 2009). An AUC value near 1 indicates a strong relationship between environmental variables in the model and the species' projected distribution, reflecting high model reliability and accuracy (Valavi et al., 2022).

The agro-climatic suitability model developed using MaxEnt software estimates the probability of species occurrence within the study area, using a scale from 0 (very low) to 1 (very high) (Khanum, Mumtaz & Kumar, 2013). Based on these probability values, cultivation suitability was categorized into four classes for mapping purposes: 0–0.25 (Unsuitable), 0.26–0.50 (Low Suitability), 0.51–0.75 (Moderate Suitability), and 0.76–1 (High Suitability) (Çoban, Örüçü & Arslan, 2020; Ab Lah et al., 2021). A change analysis was conducted using GIS to assess changes between current and future suitability areas. The results of this analysis classified the areas into four categories: Unsuitable, Stable, Gain, and Loss. The suitability maps for the current and future projections were analyzed in a GIS environment using overlay and intersection operations, and the area of each suitability category was subsequently calculated in square kilometers (km²).

3. Results

3.1. Key Environmental Variables Influencing Pistachio Cultivation Suitability

Following the correlation analysis (Figure 5), 12 variables showing a correlation coefficient above 0.85 were excluded, and 11 environmental variables with lower inter-correlation were retained to determine the potential cultivation suitability of pistachio. The model performance assessment yielded an average test AUC value of 0.927 (Fig. 7a). In this figure, the ROC curve demonstrates a clear separation between occurrence points and background data, confirming the model's high predictive accuracy. The model's standard deviation was 0.034, reflecting its stability across multiple replications. Results from the Jackknife test revealed that the bioclimatic variables with the greatest contribution to the model were precipitation seasonality (Bio15), precipitation in the driest month (Bio14), and the annual mean temperature (Bio1) (Figure 6). Among these, precipitation of the driest month (Bio14) provided the highest gain when used alone, while slope was identified as the most influential variable, as shown by the largest decrease in training gain when excluded from the model (Figure 7b).

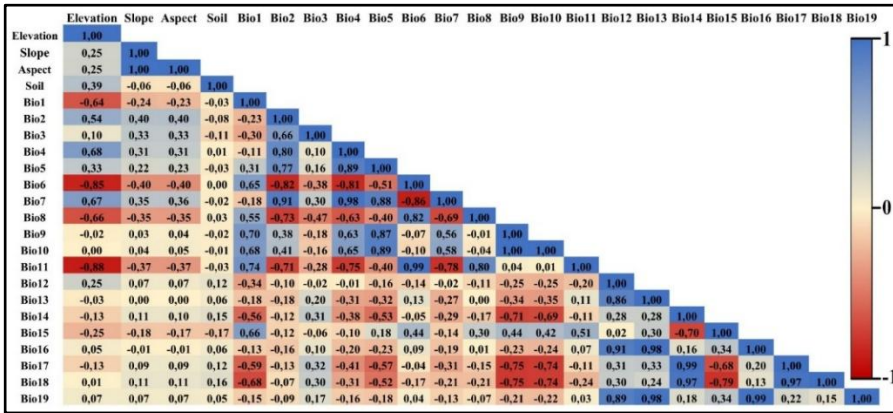


Figure 5. Pearson correlation analysis results

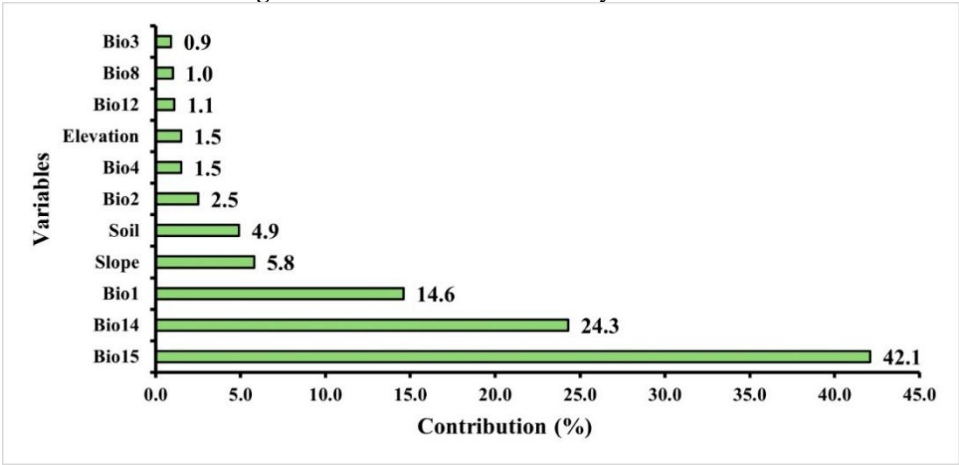


Figure 6. Environmental variables used in modeling and their percentage contribution to the model (%)

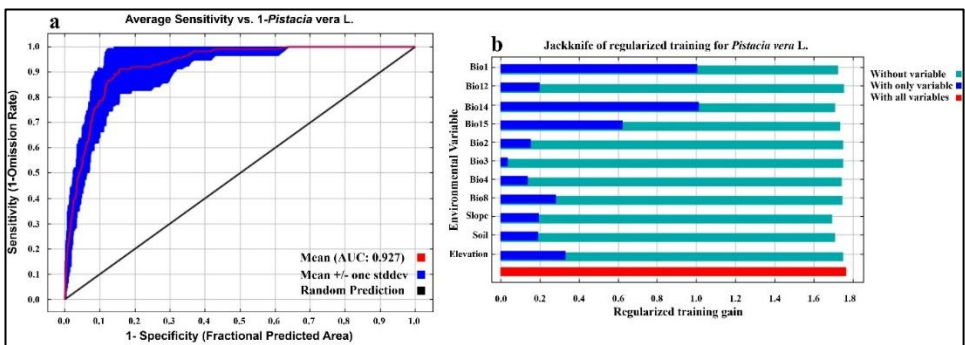


Figure 7. The AUC value and the results of the Jackknife test

3.2. Current Agro-Climatic Suitability of Pistachio Cultivation Areas

The current suitability model reveals that approximately 82% of Türkiye's total area is classified as unsuitable for pistachio cultivation. The results indicate that low, moderate, and high suitability areas are concentrated in specific regions

across the country. Low Suitability areas account for about 8% of Türkiye, while Moderate Suitability areas cover 6%. High Suitability areas make up approximately 4% of the country, with these areas primarily located in the southeastern and western regions (Table 1, Figure 8).

Table 1. Cultivation suitability area (km²) and percentage coverage by suitability classes for current and future climate scenarios.

Suitability Classes	Current (km ²)	%	SSP2-4.5 2041-2060	%	SSP2-4.5 2081-2100	%	SSP5-8.5 2041-2060	%	SSP5-8.5 2081-2100	%
Unsuitable	637,141	82.4	648,322	83.8	613,160	79.3	631,736	81.7	629,486	81.4
Low Suitability	60,861	7.9	96,764	12.5	121,930	15.8	104,543	13.5	128,557	16.6
Moderate Suitability	46,485	6.0	26,358	3.4	34,373	4.4	34,216	4.4	15,277	2.0
High Suitability	29,075	3.8	2,118	0.3	4,100	0.5	3,068	0.4	243	0.0
Total	773,563	100	773,563	100	773,563	100	773,563	100	773,563	100

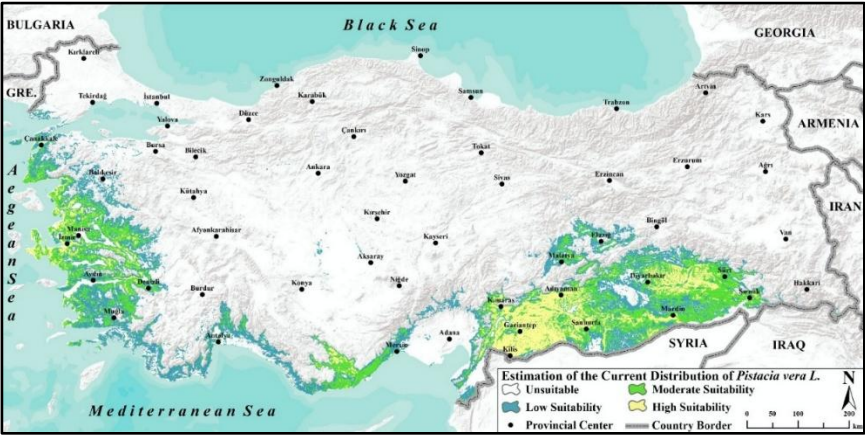


Figure 8. Current agro-climatic suitability of pistachio cultivation

3.3. Future Agro-Climatic Suitability of Pistachio Cultivation Areas

The modelling results based on future climate scenarios indicate that areas suitable for pistachio cultivation will undergo both spatial and quantitative changes. According to the SSP2-4.5 and SSP5-8.5 scenarios, it is projected that the areas suitable for cultivation may shift, with significant changes in suitability levels as a result of climate change impacts.

According to the SSP2-4.5 scenario, in the near future, areas classified as Unsuitable for pistachio cultivation may constitute 83.8% of the total area, while Low Suitability areas will make up 12.5%, Moderate Suitability 3.4%, and High Suitability a limited 0.3%. In the distant future, it is projected that the proportion of Unsuitable areas may decrease to 79.3%, with Low Suitability areas rising to 15.8%. Moderate Suitability areas are expected to increase to 4.4%, while High Suitability areas are predicted to remain at a limited 0.5%. Under this medium-optimistic scenario, the expansion of Low and Moderate Suitability areas is expected to be concentrated particularly in the southern and western parts of the country (Table 1; Figure 9).

In the SSP5-8.5 scenario, which assumes higher GHG emissions, the ratio of Unsuitable areas in the near future is projected to be 81.7%, with Low Suitability areas at 13.5%, Moderate Suitability at 4.4%, and High Suitability at 0.4%. In the distant future, it is anticipated that High Suitability areas may disappear entirely, while Unsuitable areas are expected to remain at 81.4%. Low Suitability areas may increase to 16.6%, while Moderate Suitability areas are predicted to decrease to 2% (Table 1). The model results indicate a significant rise in Low Suitability areas, particularly in the southern regions of the country, while High Suitability areas are projected to nearly vanish (Table 1; Figure 9).

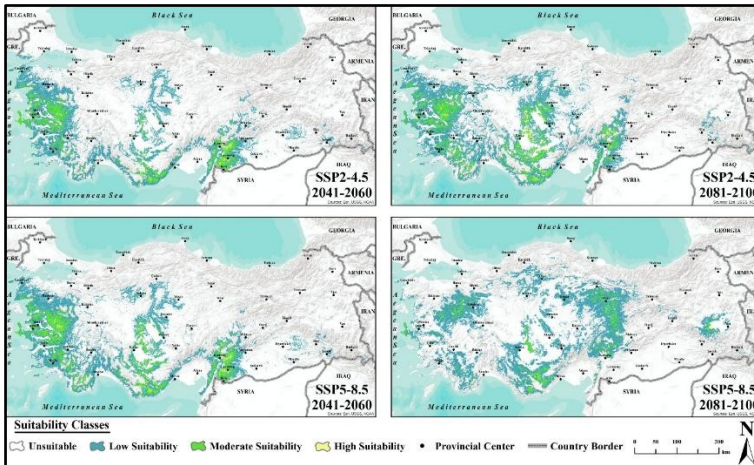


Figure 9. Projected future agro-climatic suitability classes for pistachio cultivation for 2041–2060 and 2081–2100 under SSP2-4.5 and SSP5-8.5 scenarios

The change analysis indicates that the areas expected to become suitable for pistachio cultivation in the future (gain) are primarily located in the more northern and inland parts of the country. This suggests that certain regions may become more suitable for agricultural production as a result of climate change. Conversely, the areas that are currently most suitable for cultivation but are expected to become less favorable in the future (loss) are primarily concentrated in the Southeastern Anatolia and Aegean Regions. This shift is largely attributable to factors such as temperature increases and drought conditions. Unsuitable areas currently cover a large portion of the land and are expected to expand in the future. Meanwhile, stable areas, which are currently suitable and will remain suitable, constitute a relatively small proportion of the total area (Figure 10). This indicates that current pistachio production areas are likely to undergo significant changes. According to Table 2, the percentage of areas losing suitability is notably high in both climate scenarios, with the SSP5-8.5 scenario showing a higher rate of loss, emphasizing the adverse effects of high emission levels on pistachio production. Although some areas in the gain category may become more suitable for pistachio cultivation in the future, it remains uncertain whether these gains will compensate for the current losses or how yield and quality can be maintained in these newly suitable areas.

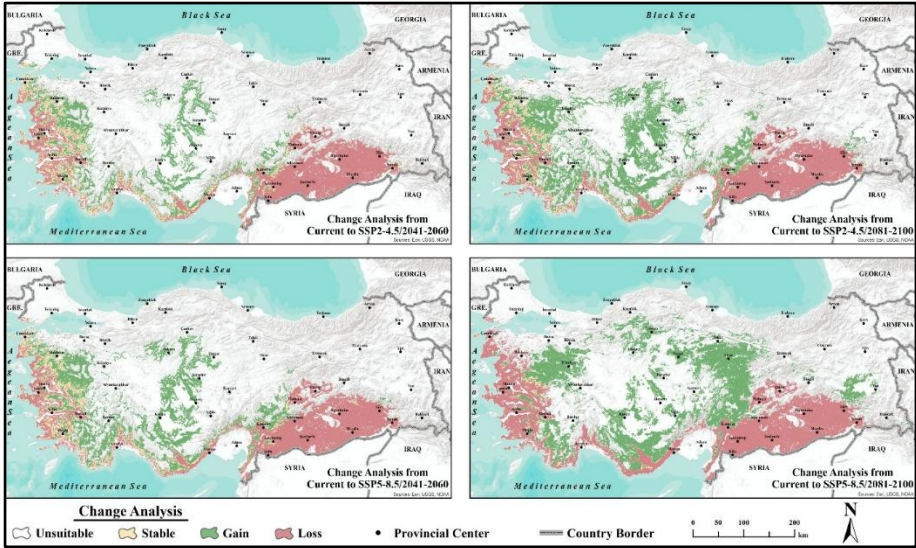


Figure 10. Projected changes in suitable areas for pistachio cultivation under SSP2-4.5 and SSP5-8.5 scenarios.

Table 2. Results of change analysis from current to the future (area in km² and %)

Classes	SSP2- 4.5 2041- 2060	%	SSP2- 4.5 2081- 2100	%	SSP5- 8.5 2041- 2060	%	SSP5- 8.5 2081- 2100	%
Unsuitable	584,848	75.6	532,206	68.8	563,743	72.9	505,884	65.4
Stable	32,214	4.2	22,063	2.9	28,844	3.7	5,222	0.7
Gain	59,513	7.7	111,719	14.4	82,581	10.7	131,925	17.1
Loss	96,988	12.5	107,575	13.9	98,394	12.7	130,532	16.9
Total	773,563	100	773,563	100	773,563	100	773,563	100

4. Discussion

MaxEnt model results indicate that the current agro-climatic suitability for pistachio cultivation in Türkiye is strongly influenced by several key bioclimatic and environmental variables. Among these, Bio15, Bio14 and Bio1 contribute the most to the model. These variables indicate that water availability during critical periods, rainfall variability, and annual mean temperature are key factors determining the agro-climatic suitability for pistachio cultivation in Türkiye. According to the model contribution percentages, Precipitation Seasonality (42.1%) is the most determinant bioclimatic variable, indicating the dependence of pistachio on a specific rainfall pattern. Increasing irregularities in the precipitation regime and prolonged dry periods in the future could threaten the sustainability of pistachio cultivation. These results highlight the critical role of precipitation for pistachio distribution, particularly under rain-fed conditions, as water availability during specific periods strongly influences the species' cultivation suitability range. Precipitation during the driest month is a critical factor, contributing 24.3% to the model. This is consistent with findings from Aloui, Neffar and Chenchouni, (2024) who also noted the significant role of the Bio14 variable in their study on *Pistacia atlantica* Desf. Precipitation during dry periods is essential for meeting the vital water needs of the species. In the context of climate change, a decrease in precipitation during these dry periods, particularly in the Southeastern Anatolia Region, could significantly affect the survival and development of pistachio trees. This is further supported by Çelik and Karabulut (2013), who found that pistachio trees in the Southeastern Anatolia Region were heavily influenced by rainfall patterns.

The Annual Mean Temperature emerges as the third most significant variable in the model, contributing 14.6%. Excessive temperature increases, particularly during the summer months, due to global warming, pose a risk of thermal stress for pistachios. Extreme temperatures can reduce the efficiency of photosynthesis, which in turn may lead to a decrease in fruit yield and product quality (Pakkish, Rahemi & Panahi, 2011; Benmoussa et al., 2017; Çelik et al., 2018; Shahraki, Caloiero & Bazrafshan, 2023). Prolonged exposure to such extreme temperatures could even result in the death of the species, as noted by Mathur et al. (2014).

Additionally, pistachios require a certain chilling period to ensure a regular growth and efficient production cycle (Rahemi & Pakkish, 2009). With rising temperatures, this chilling requirement could be compromised, further threatening pistachio production. Topographical factors, such as slope (5.8%) and soil (4.9%), have a significant influence on the spatial distribution and potential growth of pistachios. Especially topographical factors have a determining effect on microclimatic conditions (Dobrowski, 2011) and these conditions affect the growth potential of the species.

The current suitability model indicates that the most favorable habitats for pistachio cultivation are located in relatively low-altitude and warmer regions, particularly in the Southeastern part of Türkiye. Additionally, in Western Anatolia, suitable conditions for pistachio growth are found in specific areas, especially along the Aegean and Mediterranean coasts. However, high-altitude inland areas and most regions in the northern and eastern parts of the country are deemed unsuitable for pistachio cultivation due to low temperatures and other climatic constraints. These findings align with the pistachio production data from TurkStat for the years 2004-2023 (TurkStat, 2025), which show that provinces classified under High Suitability and Moderate Suitability categories also report the highest production amounts.

It was determined that areas currently classified as low suitability for pistachio cultivation will increase in the future if the climate conditions predicted by climate models materialize. On the other hand, areas in the medium and high suitability classes are expected to decrease compared to present conditions. This suggests that suitable growing areas may shift towards more inland and northern regions of the country, particularly to higher altitudes, compared to today's conditions. These findings align with studies on other *Pistacia* species in the literature. For example, Zadeh et al. (2024), revealed that the suitability of *Pistacia atlantica* may decrease under future climate scenarios. Similarly, Uzun and Sarıkaya (2023), concluded that *Pistacia terebinthus* L. may experience a significant decline in the future. Xu et al. (2023), found that suitable areas for *Pistacia chinensis* Bunge may expand towards higher latitudes and altitudes in the future. Guo et al. (2023), determined that *Pistacia chinensis* species will likely expand northward due to increasing temperatures.

Future projections suggest that climate change may significantly impact the geographical distribution of certain species (Muluneh, 2021). In this context, Akyol and Örücü (2019), revealed that the current distribution of *Cornus mas* L. in Türkiye may expand towards more northern regions in the future. Özdel et al. (2024), determined that the suitable habitats of *Olea europaea* L., which is distributed in Türkiye, may shift northward and to higher altitudes. Sarıkaya, Uzun and Turan (2024) on the other hand, found that the suitable habitats of

Arbutus unedo L. would shift to the northern parts of Türkiye, and the overall distribution area of this species would decrease significantly.

It is estimated that pistachio production areas may be reshaped due to climate change. Therefore, it is crucial to develop various strategies within the framework of climate change adaptation and sustainable development policies, as well as to conduct comprehensive planning and incentive programs for these strategies. To adapt to the environmental conditions worsened by climate change, it is important to develop pistachio varieties that are well-suited to local conditions. In this regard, selecting varieties that are particularly resistant to drought, high temperatures, extreme weather events, diseases, and pests can contribute to the sustainability of production. Additionally, selecting the appropriate irrigation methods is critical for ensuring the sustainability of production, especially in future climatic conditions where water shortages are predicted. Water-efficient systems, including drip irrigation and subsurface drip irrigation, enable the optimal utilization of water resources. Choosing the most suitable tillage methods for the species can support plant growth by enhancing soil fertility. Furthermore, controlling diseases and pests will be an essential strategy for adapting to changing climatic conditions in the future. Climate change may increase the prevalence of certain diseases and pests or alter their geographical distribution. Therefore, the effective use of biological, biotechnical, or, when necessary, chemical control methods is vital.

Proper and timely fertilization and pruning practices can help minimize yield losses by promoting healthy plant growth. Additionally, the correct application of harvesting techniques contributes to preserving product quality, while integrating agricultural technologies into production can increase productivity and reduce labor losses. Raising farmers' awareness of climate change and agricultural practices through producer training can ensure more effective implementation of adaptation strategies. These strategies are essential for pistachio production to adapt to future climate conditions. Furthermore, continuous research and the development of new solutions are crucial for the emergence of more innovative and effective adaptation strategies. It is vital that all stakeholders take swift and effective action, considering existing adaptation strategies, and that research and development efforts for innovative solutions are supported by relevant institutions or organizations. The main limitation of this study is that, although the bioclimatic variables used at 30 arc-seconds spatial resolution are sufficient for a national-scale assessment, they are less detailed for provincial-level analyses. In addition, pistachio was evaluated directly as *Pistacia vera* L. since cultivar-specific occurrence data and databases on chilling and heat requirements are not available.

5. Conclusions

This study models the potential future cultivation suitability of pistachio (*Pistacia vera* L.) in Türkiye under various climate change scenarios, considering bioclimatic variables and other environmental factors. Future projections indicate that Southeastern Anatolia, in particular, is one of the regions most susceptible to the impacts of climate change, among the areas where pistachio is cultivated. In this region, which is currently Türkiye's most significant production area, the areas suitable for pistachio cultivation are projected to shrink substantially if the predicted climate change scenarios materialize. Compared to the current cultivation suitability areas, High Suitability and Moderate Suitability zones are expected to decrease, while Low Suitability areas are anticipated to increase. If the climate conditions forecasted by future climate models occur, production areas are likely to shift towards more northern, inland, and higher-altitude regions. Furthermore, there is a possibility that the suitable areas in the western parts of the country may overlap with areas currently used for *Olea europaea* L. cultivation in the future (Özdel et al., 2024). The findings of this study are expected to contribute to estimating both the current and potential future cultivation suitability of pistachio, enhancing our understanding of the environmental factors that influence its cultivation suitability, and providing a foundation for sustainable management, conservation strategies, and rational site selection.

The findings of this study not only reveal the potential impacts of climate change but also provide an important basis for agricultural planning and policy development. These results can guide the selection of sites for new pistachio plantations, the development of adaptation strategies for existing production areas against climate risks, and the promotion of good agricultural practices for more efficient water use. Furthermore, considering the strategic importance of pistachio production for the national economy and rural development, the study offers decision-makers and producers a forward-looking framework to support sustainability and enhance economic well-being. Moreover, the study's outputs can be revisited in light of advancements in data, technological infrastructure, and methodological developments; this may enable the expansion of similar ecological and agricultural analyses in the future and the more effective planning of adaptive management strategies. In addition, future studies could employ different global circulation models and alternative machine learning algorithms to compare results and diversify modeling approaches.

6. Reference

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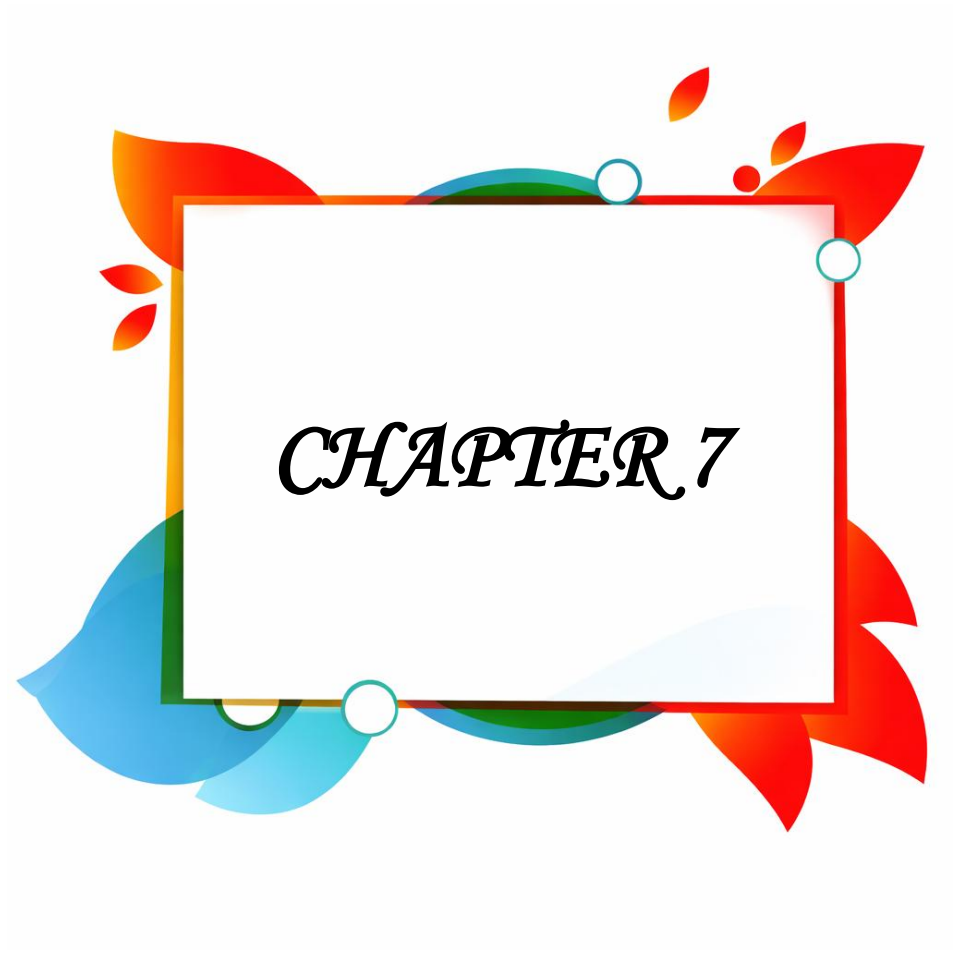
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Agricultural Value Chain Analysis and Value-Added Creation Strategies in Eastern Anatolia: The Case of İğdır Province

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INTRODUCTION

The agricultural sector occupies a pivotal position in developing economies, serving not merely as the principal livelihood source for rural populations but also as a cornerstone of food security, rural development, employment generation, and export diversification (FAO, 2019; OECD, 2021). Türkiye ranks as the largest agricultural producer in Europe and among the top 10 globally (TUIK, 2024). Nevertheless, this substantial production capacity has not translated commensurately into enhanced producer welfare, particularly in the rural areas of Eastern Anatolia (World Bank, 2020).

Located at Türkiye's easternmost point, İğdır province shares borders with Nakhchivan Autonomous Republic, Iran, and Armenia, occupying a strategically significant geopolitical position. Notwithstanding its relatively modest demographic profile with an area of 358,700 hectares and a population of 206,857 (TÜİK, 2024), its distinctive micro-climatic conditions facilitate the cultivation of a diverse array of horticultural crops that are otherwise unviable in the broader Eastern Anatolian context (Alım & Kaya, 2005). Situated in the Aras River valley at an altitude of 800-900 meters, the province reaches temperature values substantially exceeding the regional average, enabling the production of apricots, watermelons, melons, tomatoes, eggplants, and peaches (İğdır Provincial Directorate of Agriculture and Forestry [ITOM], 2026).

The province has 104,648 hectares of agricultural land with 8,242 Farmer Registration System (ÇKS) registered enterprises, and approximately 35% of the provincial population is employed in agriculture (TUIK, 2024; ITOM, 2026). İğdır ranks 8th nationally in apricot production (39,534 tons), 6th in alfalfa production (735,409 tons), and 14th in small ruminant livestock (1,254,673 head)

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(TUIK, 2024; ITOM, 2026). Despite this considerable production capacity, producer income remains substantially below its theoretical potential, attributable to fragmented marketing chains, inadequate storage infrastructure, the predominant sale of products in raw unprocessed form, the absence of packaging and processing facilities, attenuated farmer bargaining power, and constrained access to modern agricultural technologies.

The principal objective of this investigation is to systematically examine the agricultural product marketing, storage, and value creation processes in Iğdır, delineate the underlying constraints, and formulate evidence-based policy recommendations. The study provides analysis at both micro (enterprise) and meso (regional) levels, benchmarking against successful national and international paradigms.

CONCEPTUAL FRAMEWORK AND LITERATURE REVIEW

Agricultural Marketing and Value Chain Approach

Agricultural marketing constitutes a multifaceted process encompassing the flow of products, information, and value between producers and consumers. While the traditional marketing approach positions the producer as a "price taker," the contemporary value chain paradigm advocates for substantive producer engagement in the value creation process (Porter, 1985). The Republic of Türkiye Ministry of Agriculture and Forestry (2022) sector report documented that the producer-consumer price differential has exhibited a persistent widening trajectory, with the proliferation of intermediaries identified as the principal contributing factor. Demircan, Hatırlı, and Aktaş (2004), studying cherry marketing in Isparta, established that the attenuated bargaining power of small-scale enterprises exerts a deleterious effect on producer income.

The predominant marketing of agricultural products in their raw, unprocessed state effectively cedes the entirety of potential value addition to intermediary actors (Republic of Türkiye Ministry of Agriculture and Forestry, 2022). In the absence of packaging, standardization, and branding, products are precluded from accessing retail shelves, export markets, and consumer trust mechanisms.

Post-Harvest Losses, Cold Chain, and Digital Agriculture

According to FAO (2019), approximately one-third of global food production is subject to post-harvest losses or wastage. UNEP and FAO (2022) report that the lack of cold chain infrastructure leads to the loss of around 12% of global food production, and that strategic investment in sustainable cold chains can substantially reduce these losses in emerging economies. The licensed warehousing system in Türkiye operates under Law No. 5300, with a total national capacity of 7 million tons across 177 locations (TOBB, 2024).

Digital agriculture enables more scientific and precise agricultural decision-making through sensors, satellite imagery, and data analytics (Wolfert, Ge, Verdouw, & Bogaardt, 2017). Smart irrigation systems can achieve 30-50% water savings, while modern fertilization based on soil analysis can increase productivity by 20-40% and reduce input costs by 15-25% (Klerkx, Jakku, & Labarthe, 2019). However, the diffusion of these technologies in Eastern Anatolian rural areas faces significant barriers (Şahin Demirel & Erik, 2024).

Geographical Indications and Cooperatives

Geographical indications (GI) constitute an important intellectual property instrument that protects region-specific products and confers marketing advantages (Türkpatent, 2025). According to the FAO and EBRD analysis of nine worldwide case studies, GI registration and branding can augment the value of the final product by 20-50% (Vandecandelaere et al., 2018). Özdemir (2005) established that cooperatives possess the potential to enhance producer income, yet governance deficiencies have impeded the full realization of this potential. The TUSIAD and FAO (2026) report confirms that cooperatives face structural challenges in market integration and institutional capacity.

MATERIALS AND METHODS

The present investigation employs a mixed-methods approach, drawing upon both primary and secondary data sources. Primary data were obtained from the ITOM (2026) official Briefing Report and the Iğdır Commodity Exchange Bulletin Reports for the 2019-2025 period (Iğdır Commodity Exchange, 2025). Secondary data sources include TUIK (2024), TKDK (2025), TARSIM (2025), Türkpatent (2025), FAO (2019), World Bank (2020), UNEP & FAO (2022), Vandecandelaere et al. (2018), OECD (2021), and academic studies by Demircan et al. (2004), Özdemir (2005), Şahin Demirel and Yercan (2022), Aşkan and Dağdemir (2016), Şahin Demirel and Erik (2024), Wolfert et al. (2017), and Klerkx et al. (2019).

The analytical framework encompasses descriptive statistical analysis, cross-sectional comparative analysis, and Porter's (1985) value chain approach. Cold chain performance indicators were subjected to tripartite comparative evaluation across EU average, Türkiye average, and Iğdır provincial data.

FINDINGS

General Overview of Iğdır Agriculture

According to TUIK (2024) and ITOM (2026), Iğdır province has 104,648 hectares (1,046,475 decares) of agricultural land, constituting approximately 23% of the province's total area. There are 8,242 ÇKS-registered enterprises and 11,766 livestock enterprises. The Iğdır Plain, with 694,345 decares, holds "major plain" status (ITOM, 2026).

Table 1. Leading Crop Products in Iğdır Province (2024)

Product	Area (da)	Production (tons)	Nat. Rank	Share (%)	Group
Alfalfa	141,347	735,409	6th	4.42	Fodder
Wheat	172,000	58,309	59th	-	Cereal
Apricot	41,645	39,534	8th	3.11	Fruit
Watermelon	10,330	41,381	17th	1.29	Vegetable
Tomato	9,301	36,733	33rd	0.45	Vegetable
Corn (Grain)	34,589	35,171	29th	0.43	Cereal

Source: TUIK (2024); ITOM (2026).

As evidenced in Table 1, the preponderance of cultivated area in Iğdır is allocated to fodder crops, substantiating the inference that the province's primary livelihood is livestock farming (ITOM, 2026). The Şalak variety constitutes approximately 85% of apricots grown, distinguished by its unique flavor profile under exceptional micro-climatic conditions (Alım & Kaya, 2005; Kaya, Pehlivan, Doğru, & Bozhüyük, 2013).

Land Structure, Farm Scale, and Technology Access

In Iğdır, 75% of farm enterprises are below 5 hectares. The average farm size of 4.1 hectares constitutes a significant impediment to mechanization compared to the EU average of 16.1 hectares (OECD, 2021; World Bank, 2020). Moreover, a notable proportion of producers exhibit constrained access to contemporary agricultural methodologies. Digital agriculture, precision irrigation, and evidence-based fertilization practices have not been sufficiently adopted (ITOM, 2026; Şahin Demirel & Erik, 2024). The primary determinants include information asymmetries, high perceived investment costs, and insufficient technical support (Klerkx et al., 2019).

Marketing Channels, Price Formation, and Farmer Bargaining Power

Empirical findings indicate that agricultural product marketing channels in Iğdır remain predominantly rudimentary, with 52% of producers selling to village traders at the farm gate and only 8% utilizing cooperative channels (ITOM, 2026). A disproportionate share of production is marketed in its raw, unprocessed state, with the farm-gate price constituting merely 25-30% of the consumer price (Republic of Türkiye Ministry of Agriculture and Forestry, 2022; ITOM, 2026).

Analysis of the Iğdır Commodity Exchange Bulletin Reports (2019-2025) reveals significant price dynamics for selected agricultural products, as summarized in Table 2.

Table 2. Iğdır Commodity Exchange Selected Product Prices (2019-2025, TL/kg)

Year	Apricot	Juice Grade*	Alfalfa (Min)	Alfalfa (Max)	Change (%)**
2019	6.45	0.54	0.45	2.06	-
2020	7.00	2.00	0.99	1.53	+8.5
2021	11.00	4.00	1.59	1.68	+57.1
2022	22.00	5.00	1.17	3.78	+100.0
2023	32.50	2.40	3.15	5.65	+47.7
2024	45.00	12.00	6.99	7.22	+38.5
2025	66.50	9.00	7.50	8.50	+47.8

*Source: Iğdır Commodity Exchange (2025). Bulletin Reports (2019-2025). *Juice Grade: Industrial quality apricot for fruit juice processing. **Change: Year-on-year percentage change in apricot price.*

As demonstrated in Table 2, the Iğdır Commodity Exchange registered apricot price escalated from 6.45 TL/kg in 2019 to 66.50 TL/kg in 2025, representing an approximately 10.3-fold nominal increase over the seven-year period (Iğdır Commodity Exchange, 2025). However, a substantial proportion of this nominal appreciation is attributable to inflationary pressures, with cumulative consumer inflation in Türkiye exceeding 400% during the same period (TUIK, 2024), indicating that real producer income growth has been considerably more circumscribed. The persistently depressed pricing of juice-grade apricots relative to table-grade apricots furnishes compelling evidence that the marketing of raw, lower-quality produce substantially erodes producer income. The sustained upward trajectory in alfalfa prices reflects the escalating fodder demand driven by the province's expanding livestock sector.

The erosion of farmer bargaining power represents perhaps the most consequential manifestation of this structural deficiency. Small-scale enterprises cannot assume a price-setting position against large buyers, and the absence of adequate packaging, processing, and branding infrastructure compounds this predicament (UNEP & FAO, 2022; Vandecandelaere et al., 2018; TKDK, 2025).

Storage Infrastructure and Cold Chain

Iğdır's cold storage capacity stands at approximately 12,000 tons. Sixty percent of fresh fruit and vegetable production enters the market without storage, with post-harvest losses of 25-35% representing approximately three times the EU average (FAO, 2019; UNEP & FAO, 2022; ITOM, 2026).

Table 3. Cold Chain Indicators: International Comparison

Indicator	EU Avg.	Türkiye Avg.	Iğdır
Cold Storage Cap. (kg/person)	120	42	18
Product Loss Rate (%)	8-12%	22%	28-35%
Refrigerated Vehicles (per 100 km ²)	4.2	1.1	0.3
Cold Chain Coverage (%)	85%	45%	20%

Source: UNEP & FAO (2022); FAO (2019); ITOM (2026).

Grain Licensed Warehouse Status

The Alagöz Holding's Kaan Licensed Warehousing facility (55,000 tons) and TMO's licensed warehouse (5,500 tons) provide a combined 60,500-ton grain licensed warehouse capacity (ITOM, 2026). The system enables producers to obtain Electronic Warehouse Receipts (ELÜS) for bank loan collateral (TMO, 2021; TOBB, 2024).

Value Added, Geographical Indications, and Livestock

Fresh apricot farm-gate price stands at 4.8 TL/kg while dried apricot reaches 55 TL/kg and apricot kernel for export attains 90 TL/kg (Republic of Türkiye Ministry of Agriculture and Forestry, 2022), indicating that processing chain establishment could augment producer income by 10-19 fold. Six GI products are registered in the province (Türkpatent, 2025), though no EU-approved GI product exists.

Iğdır possesses 112,176 cattle and 1,254,673 small ruminants, with annual milk production of 162,000 tons; yet only 8% undergoes facility processing (ITOM, 2026). Research on dairy cattle enterprises in the TRA1 region has

demonstrated that production costs and profitability are significantly influenced by support mechanisms and cooperative membership (Aşkan & Dağdemir, 2016).

Cooperatives, Support, and Financing

Iğdır has merely 3 agricultural development cooperatives with 100 partners (ITOM, 2026). Successful models including Tire Süt Cooperative (UN-recognized), Marmarabirlik (3.4 billion TL payments), TARIŞ, Ovacık, Ezogelin, and Gödençe offer replicable frameworks (TUSIAD & FAO, 2026). IPARD III utilization in Iğdır stands at only 18%, while TARSIM agricultural insurance covers merely 2.5% of farmland (ITOM, 2026; TKDK, 2025; TARSIM, 2025).

DISCUSSION AND EVALUATION

When the research findings are synthesized holistically, it becomes manifest that Iğdır's agriculture exhibits a "strong production, weak marketing" structural configuration, consistent with the Republic of Türkiye Ministry of Agriculture and Forestry's (2022) sectoral assessments.

The Iğdır Commodity Exchange data (Table 2) reveal that apricot prices appreciated 10.3-fold nominally during 2019-2025. However, given that cumulative consumer inflation in Türkiye surpassed 400% during the same period (TUIK, 2024), real producer income growth has been markedly more constrained. The substantial price differential between table-grade and juice-grade apricots constitutes empirical evidence that raw, low-quality product marketing substantially diminishes producer income (Iğdır Commodity Exchange, 2025).

The predominant marketing of products in raw form, compounded by the dearth of packaging and processing facilities, effectively nullifies the producer's value-addition capacity. The findings of Demircan et al. (2004) corroborate this assessment. The weakness of farmer bargaining power is inextricably linked to the inadequate cooperative structure (Özdemir, 2005).

The insufficient adoption of digital agriculture, precision irrigation, and modern fertilization technologies constitutes a substantial opportunity cost. Wolfert et al.'s (2017) findings regarding digital agriculture's potential to enhance productivity by 20-40% are equally applicable to Iğdır. The availability of 50-65% grant support under IPARD Measure 1 represents a significant opportunity (TKDK, 2025).

The "quadrangle" model integrating cooperative formation, government investment, GI branding, and modern agricultural technologies offers a holistic and integrated solution architecture for Iğdır (World Bank, 2020; OECD, 2021).

CONCLUSION

The agricultural sector of Iğdır province exhibits substantial production potential; however, its value chain remains structurally fragmented. Iğdır Commodity Exchange data demonstrate that apricot prices rose from 6.45 TL to 66.50 TL nominally during 2019-2025, yet real income growth has been constrained by inflation (Iğdır Commodity Exchange, 2025). The predominant sale of products in raw form, packaging deficiencies, attenuated farmer bargaining power, and insufficient access to modern agricultural technologies constitute the principal structural impediments. Six interdependent strategic action areas are recommended; (1) Producer Organization: Establishment of product-specialized cooperatives and adaptation of Tire Süt and Marmarabirlik models. (2) Storage and Cold Chain: A minimum of 5,000 tons of additional cold storage under IPARD III and ELÜS system expansion. (3) Processing, Packaging, and Branding: Apricot drying facilities, modern packaging centers, and active GI promotion. (4) Contract Farming: Pilot projects and increased TARSIM coverage. (5) Digital Agriculture: Precision irrigation, smart farming, and IoT-based monitoring systems. (6) Information Systems and E-commerce: Real-time price information and agricultural e-marketplace platforms.

In summation, the realization of Iğdır agriculture's potential necessitates the concerted and integrated reinforcement of the cooperative formation, government investment (IPARD III), GI branding, and modern agricultural technologies quadrangle. The synergistic deployment of these four pillars is projected to catalyze a three- to fivefold augmentation of regional value added.

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