CURRENT APPROACHES IN AGRICULTURAL RESEARCH

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Current Approaches in Agricultural Research

PREFACE

Our book titled "**Current Approaches in Agricultural Research**" consisting of ten chapters, aims to contribute to the scientific development of the discipline by bringing together international academic studies and theoretical approaches in the field of agricultural sciences. In addition to strengthening the theoretical foundation of the field, the chapters presented in the book offer a comprehensive perspective that will serve as a guide for future research. We extend our sincere thanks to the esteemed academics who contributed to the compilation of chapters from different disciplines and to İKSAD Publishing House for their support in the publication of this work.

We state that all academic and legal responsibility regarding the chapter contents belongs to the authors, and we hope that this book, which aims to open new horizons, will contribute to scientific knowledge.

December, 2025

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CHAPTER 1

WAXY MAIZE (*Zea mays* L. ssp. *ceratina*) BOTANICAL, MORPHOLOGICAL AND PHYSIOLOGICAL CHARACTERISTICS

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INTRODUCTION

Waxy maize (*Zea mays L. ssp. ceratina*) stands out as one of the most distinctive subspecies among maize varieties in terms of starch composition. The presence of nearly 100% amylopectin in its endosperm places this plant in a strategic position for both basic sciences and applied agriculture and industry. Due to this unique characteristic, waxy maize is valued as a crucial raw material not only in scientific research but also in food, feed, and industrial production.

First identified in 1909 within local populations of Chinese origin, waxy maize derives its name from the characteristic "cereous" (waxy) reaction its starch exhibits when treated with iodine solution (Collins, 1909). This trait is one of the most fundamental phenotypic markers distinguishing waxy maize from other maize types and directly demonstrates the uniqueness of its starch structure.

These genetic and biochemical properties make waxy maize a vital feedstock for various sectors, including the food industry, livestock feed production, paper and textile industries, and bioplastic manufacturing. The morphological and physiological structure of the plant has evolved to ensure high yield and quality in harmony with starch accumulation. Consequently, waxy maize is a valuable agricultural resource on both national and international scales, from the perspectives of both research and production.

1. BOTANICAL, MORPHOLOGICAL, AND PHYSIOLOGICAL CHARACTERISTICS

1.1. Phenotypic Selection and Early Botanical Descriptions

The foundation of phenotypic selection and classification approaches in maize was laid through systematic botanical and morphological observations conducted in the early 20th century. The first comprehensive studies aimed at the scientific description of waxy maize were carried out by Collins (1909) on local maize populations of Chinese origin. In these studies, Collins demonstrated that waxy maize is distinguished from other Zea mays subspecies primarily through the morphological, optical, and physical properties of the kernel endosperm, rather than its vegetative growth characteristics.

1.2. Morphological and Optical Properties of Waxy Endosperm

Collins' detailed investigations revealed that the waxy maize endosperm exhibits a structure significantly different from the normal, flint, and dent maize types defined up to that period. The researcher emphasized that while this endosperm type is closely related to the vitreous (horny) endosperm in terms of anatomical positioning and tissue organization, it diverges significantly in its optical and physical properties.

Although the waxy endosperm appears less glassy than the vitreous endosperm, it shows great similarity in terms of hardness; however, it is distinguished by its dull, smooth, and distinctly opaque surface.

1.3. Relationship Between Endosperm Structure and Starch Granule Morphology

At the core of these distinctive optical properties lie the granule morphology and molecular structure of the starch stored in the endosperm. Microscopic and biochemical studies conducted in subsequent years revealed that the starch granules in waxy maize endosperm exhibit a more homogeneous, highly branched structure that causes irregular light refraction. This condition results in the endosperm acquiring a hazy and waxy appearance rather than a glassy luster.

1.4. Terminology and Diagnostic Chemical Reactions

To define this unique endosperm type within classical maize classifications, Collins proposed the use of the terms "cereous" or "waxy endosperm." This terminology is based not only on a visual analogy but also on the physical behavior and chemical content of the endosperm tissue. Indeed, the characteristic reddish-brown reaction of waxy maize kernels when treated with an iodine-potassium iodide solution has been accepted as a crucial diagnostic criterion supporting this definition.

1.5. Starch Composition and Physiological Consequences

Detailed analyses in later years revealed that this difference in the endosperm structure of waxy maize stems from a specific genetic mutation occurring in the starch biosynthesis pathways. In waxy maize, nearly all of the endosperm starch is composed of amylopectin, with the linear amylose fraction being either negligible or below 5%. This condition fundamentally alters the physical behavior of the starch granules.

Amylopectin-dominant starch granules exhibit higher swelling capacity, gel stability, and viscosity maintenance during thermal processing. These properties cause the waxy maize endosperm to differentiate both optically and technologically. Examinations at the electron microscopy level have shown that waxy maize starch granules possess more irregular surfaces and highly branched molecular structures.

Table 1. Comparison of morphological and structural properties of starch granules in normal maize and waxy maize endosperm.

Property	**Normal Maize (Zea mays L.)**	**Waxy Maize (*Zea mays L. var. ceratina*)**
Starch Composition	Amylose (20–30%) + Amylopectin (70–80%)	Almost exclusively amylopectin (>95%)
Granule Shape	Polygonal, angular granules	More spherical or semi-spherical granules
Granule Surface	Relatively smooth and homogeneous	Relatively irregular, rougher surface
Granule Packing	Tight and compact	Looser and heterogeneous
Inter-granular Space	Minimal	More pronounced
Granule Boundaries (SEM)	Distinct and clear	Less distinct, occasionally irregular
Iodine ($I–KI_2$) Reaction	Blue–black color (amylose–iodine complex)	Reddish–brown color (amylopectin-dominant)
Swelling Power	Low to medium	High

Property	**Normal Maize (Zea mays L.)**	**Waxy Maize (*Zea mays L. var. ceratina*)**
Gelatinization Behavior	Firmer gel structure	Softer gel, higher peak viscosity
Functional Implication	More resistant to enzymatic hydrolysis	Higher digestibility and enzymatic accessibility

Source: Compiled by the author (based on Whistler et al., 1984; Tester et al., 2004).

1.6. Genetic Control: The waxy (wx) Gene

The characteristic endosperm structure of waxy maize is controlled by the recessively inherited waxy (wx) gene, which is localized on chromosome 9. In normal maize, this gene regulates the synthesis of the Granule-Bound Starch Synthase (GBSS) enzyme, which is responsible for amylose biosynthesis. As a result of a mutation in the wx gene, the GBSS enzyme loses its functionality, leading to the absence of amylose synthesis within the endosperm tissue (Nelson, 1968; Coe et al., 1988).

1.7. Endosperm Development and Metabolic Specialization

This genetic mechanism has led to waxy maize being evaluated as a unique subspecies, not only morphologically but also physiologically and metabolically. During endosperm development, the redirection of carbohydrate metabolism predominantly toward amylopectin accumulation directly influences the grain-filling process, starch granule organization, and final product quality.

1.8. Breeding Studies and Modern Waxy Maize Varieties

The morphological descriptions established by Collins in 1909 facilitated the scientific recognition of waxy maize; however, the agricultural and industrial potential of this maize type remained limited until the mid-20th century. Beginning specifically in the 1930s in the United States, followed by developments in China, breeding programs replaced low-yielding local waxy populations with high-yielding hybrid waxy maize varieties.

Today, modern hybrid waxy maize can reach yield levels close to those of conventional dent maize. In contrast, they offer much higher added value in food, feed, and industrial applications due to their unique starch structure. Collins' early morphological observations formed the foundation for these advancements, paving the way for waxy maize to become a focal point of multidisciplinary research spanning from botany to molecular biology (Seydoşoğlu and Başbağ, 2024; Karaman et al., 2024).

2. BOTANICAL CHARACTERISTICS

Waxy maize (*Zea mays L. var. ceratina*) is an annual herbaceous crop belonging to the Poaceae (Gramineae) family. Genetically, it possesses a diploid structure with a chromosome count of 2n = 20. Although its general botanical organization aligns with other Zea mays subspecies, it is distinctly characterized by the morphological, physiological, and biochemical properties of its kernel endosperm. The botanical features of waxy maize are evaluated within the framework of its root system, stem and leaf morphology, inflorescence structure, and kernel characteristics.

2.1. Root System

Waxy maize possesses a fibrous root system typical of the species. The primary root, which develops during the early stages, loses its function shortly after germination, while the nodal roots developing from the nodes constitute the plant's fundamental root system. This structure ensures a strong interaction between the plant and the soil from both physiological and mechanical perspectives.

Under favorable soil conditions, these roots can reach depths of 1–2 m and spread across a wide horizontal volume. This architecture enables the plant to utilize water and nutrients from the deeper layers of the soil profile, thereby granting a relative tolerance to drought stress (Shiferaw et al., 2011). Adventitious (brace) roots developing from nodes near the soil surface enhance the plant's resistance to lodging, providing stability against wind, heavy rainfall, and loose soil conditions. These roots also play a vital role in the uptake of nutrients with limited mobility, such as nitrogen and phosphorus.

2.2. Stem and Leaves

The stem of waxy maize is a cylindrical structure composed of nodes and internodes. While the average plant height generally ranges between 2–3 m, it varies significantly depending on the genotype and cultivation conditions. The relatively high lignin content in the stem tissue grants mechanical strength and enhances lodging resistance.

Regarding leaf morphology, in the original waxy maize forms described by Collins (1909), it was reported that leaves developing from the upper nodes were more upright, while the lower leaves exhibited a spreading and drooping structure. Additionally, it was noted that the first four to five leaves at the base develop on the same side of the plant. This phyllotaxy was emphasized as an adaptive trait associated with high drought resistance during the flowering period, distinguishing waxy maize from other Zea mays subspecies (Collins, 1909). In modern commercial hybrid waxy maize varieties, the leaves are typically long, wide, and lanceolate, with widths ranging from 10–15 cm and lengths between 50–100 cm. The broad leaf surface area increases photosynthetic efficiency, positively impacting carbon assimilation and, consequently, grain yield.

2.3. Flowering and Pollination

Similar to other maize types, waxy maize is a monoecious plant, where male and female flowers are located on the same plant but in separate organs. The male flowers are situated on the tassel at the apex of the plant and produce large quantities of pollen, which is transported by wind. The female flowers are located on the ears developing in the leaf axils. Following pollination and fertilization, the kernels develop in a spiral arrangement around the cob axis. Successful pollination is a direct determinant of ear filling and kernel count.

2.4. Kernel Structure and Endosperm Properties

Waxy maize kernels are generally round, plump, and smooth-surfaced, exhibiting a dull, opaque, and characteristic waxy appearance. Kernel color varies among yellow, white, red, or purple tones depending on the genotype. The most critical feature distinguishing waxy maize is the chemical composition of the starch in the kernel endosperm. While the amylopectin fraction constitutes approximately 70–75% of the starch in normal maize, it reaches 95–100% in waxy maize (Watson, 2003).

This characteristic endosperm structure is controlled by a single recessively inherited gene, localized on chromosome 9, referred to as waxy (wx) or wx-c for forms of Chinese origin (Coe et al., 1988). A mutation in the wx gene eliminates the activity of the Granule-Bound Starch Synthase (GBSS) enzyme, preventing the synthesis of amylose. Therefore, the waxy maize endosperm consists exclusively of branched starch molecules (amylopectin). Another distinguishing feature of waxy starch is its unique coloration and expansion reaction when treated with an iodine solution, which serves as a reliable diagnostic chemical indicator (Weatherwax, 1922).

While the morphological characteristics of waxy maize align with classical maize types in general structure, they directly influence yield potential, harvestability, and industrial suitability. However, morphological evaluation in waxy maize should focus on plant and ear architecture rather than just endosperm characteristics.

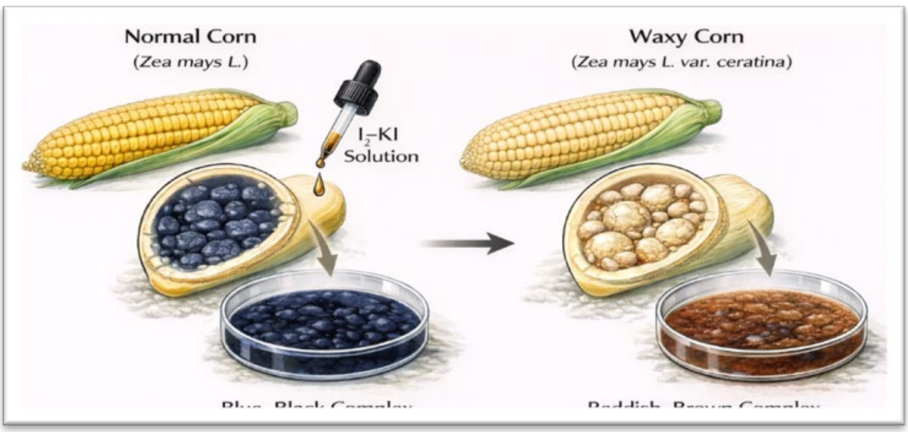

Figure 1. Comparison of color reactions in the endosperm of normal maize and waxy maize based on starch composition using the $I–KI_2$ (iodine–potassium iodide) test (adapted from Whistler et al., 1984).

2.5. Ear Morphology

In waxy maize, the ears are generally positioned at the middle-to-lower part of the plant height. This placement provides a significant morphological advantage by lowering the plant's center of gravity, thereby increasing resistance to lodging. Typically, each plant produces a single ear; however, under optimal environmental and nutritional conditions, two ears may occasionally develop (Sabagh et al., 2021; Seydoşoğlu and Turan, 2023).

The ear length generally varies between 15–25 cm, while the ear diameter and fullness differ depending on the genotype. The number of kernel rows on the ear is mostly between 18–20, and this value exhibits a more regular and homogeneous structure in modern hybrid waxy maize varieties. The cob axis (rachis) is robust and well-developed, contributing to the reduction of mechanical losses during harvesting and processing.

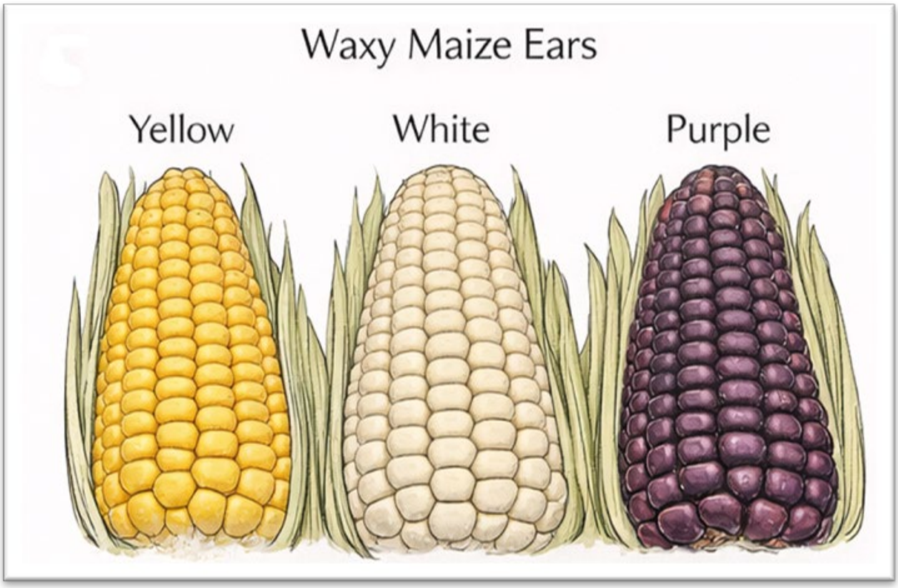

Figure 2. Ear types based on kernel color in waxy maize (*Zea mays L. ssp. ceratina*): yellow, white, and purple forms (adapted from Hallauer et al., 2010)2.2. Kernel Arrangement and External Morphology

In waxy maize, kernels exhibit a regular spiral arrangement around the cob axis. Homogeneous kernel distribution positively impacts both ear fullness and industrial processability. The kernels are generally round or slightly oval, with smooth and opaque outer surfaces.

The structure of the pericarp (kernel coat) possesses sufficient durability to maintain kernel integrity during harvesting and storage. The waxy appearance primarily stems from the endosperm structure and is considered a secondary trait in defining external morphology. Therefore, in the morphological classification of waxy maize, kernel shape and arrangement are emphasized, while starch composition is treated as a biochemical criterion.

2.6. Relationship Between Morphological Traits, Breeding, and Yield

The industrial potential of the waxy (wx) mutant, identified in China in 1908, was only fully recognized in the 1930s through breeding programs conducted in the United States. Cross-breeding studies initiated at Iowa State University in 1936 marked a significant turning point in transforming low-yielding local waxy populations into high-yielding hybrid varieties (Dickerson, 2003).

In modern hybrid waxy maize varieties developed today:

- Plant and ear heights have been optimized,
- Ear length and kernel row numbers have been increased,
- Morphological homogeneity has been achieved.

Due to these advancements, the grain yield of waxy maize has closely approached that of conventional dent maize, reaching equivalent levels under certain environmental conditions (Fergason, 2001). Consequently, waxy maize has transitioned from being a specialty genetic material to a cultivated crop suitable for commercial production.

3. PHYSIOLOGICAL CHARACTERISTICS

The physiological properties of waxy maize are defined by photosynthetic efficiency, carbohydrate metabolism, water and nutrient utilization strategies, and responses to stress conditions. These traits directly influence both the environmental adaptation of waxy maize and the unique starch structure that emerges during the grain-filling process.

3.1. Photosynthetic Capacity and Carbon Assimilation

Waxy maize, like other *Zea mays* subspecies, utilizes the C_4 photosynthetic mechanism. In this mechanism, CO_2 is initially fixed in mesophyll cells via the phosphoenolpyruvate carboxylase (PEPC) enzyme and subsequently incorporated into the Calvin cycle by the Rubisco enzyme within the bundle sheath cells. This dual-cell system significantly limits photorespiration, thereby increasing the net photosynthetic rate, particularly under high temperatures and intense light conditions.

A significant portion of the assimilates obtained from photosynthesis is directed toward the endosperm tissue during the generative stage and is primarily utilized in amylopectin synthesis. This indicates that carbon flow is physiologically channeled toward starch biosynthesis.

3.2. Carbohydrate Metabolism and Starch Biosynthesis

The most distinctive physiological feature of waxy maize is the redirection of carbohydrate metabolism toward amylopectin-dominant starch accumulation. The inactivity of the Granule-Bound Starch Synthase (GBSS) enzyme due to the *wx* gene mutation prevents amylose synthesis; conversely, highly branched amylopectin molecules are synthesized via branching enzymes (SBE I and SBE II).

This physiological orientation results in starch granules acquiring properties such as rapid swelling, high water-binding capacity, and gel stability during grain filling. Consequently, carbohydrate metabolism in waxy maize diverges from conventional maize types not only in quantity but also in molecular structure.

3.3. Water Use Physiology and Transpiration Control

Water use physiology in waxy maize is highly optimized through the interaction of the C_4 photosynthetic system and a well-developed root structure. The sensitive regulation of stomatal apertures in response to environmental conditions limits transpiration losses and enables higher biomass production per unit of water. The waxy cuticle layer on the leaf surface is considered an additional physiological adaptation to reduce water loss.

3.4. Nutrient Uptake, Transport, and Physiological Sensitivity

Waxy maize physiology is highly sensitive to nitrogen (N), phosphorus (P), and potassium (K) nutrition. Nitrogen enhances photosynthetic capacity through chlorophyll synthesis and leaf area development, while phosphorus plays a critical role in energy metabolism and root growth. Potassium serves as a primary regulator of stomatal movements, water balance, and carbohydrate transport. Nutrient uptake is most intensive during the jointing, tasseling, and grain-filling stages.

4. APPLICATIONS AND ECONOMIC IMPORTANCE

Waxy maize (*Zea mays* ssp. *ceratina*) is currently valued as a strategic industrial agricultural product due to its unique starch structure and versatile processability.

4.1. Yield Performance and Breeding Advancements

Modern waxy maize varieties are now largely equivalent to dent maize in terms of grain yield, with average yield differences not exceeding 5% in most environments (Fergason, 2001). Breeding programs, particularly in China over the last two decades, have focused on multi-faceted selection strategies to increase both yield and kernel quality. Efforts to increase oil content by enlarging the embryo have led to the successful breeding of High Oil Corn (HOC) and High Oil Waxy Corn (HOWC) types (Ding et al., 2006).

4.2. Chemical Composition of Maize Types

Waxy maize distinguishes itself from normal maize in both starch and energy content. A starch content exceeding 68% and high metabolizable energy (ME) values make it attractive for both feed and industrial starch production. In HOWC types, the significant increase in crude oil and protein ratios provides advantages in animal nutrition and functional food applications (Akay & Jackson, 2001; Zarate et al., 2004).

4.3. Waxy Maize Starch and Industrial Modification

Waxy maize starch possesses unique rheological and functional properties because it consists exclusively of amylopectin. This structure grants high swelling capacity, superior gel stability, and viscosity maintenance after thermal processing. While conventional maize starch often requires expensive physical and chemical modifications for industrial use, waxy maize starch requires fewer such processes due to its natural properties (Fergason, 2001; Klimek-Kopyra et al., 2012).

4.4. Food, Feed, and Industrial Sectors

In the food industry, waxy starch is widely used as a thickener in sauces and soups, where its high water absorption capacity improves mouthfeel and shelf stability. It is also popular among athletes and bodybuilders as a rapid carbohydrate source for glycogen replenishment. In the paper and textile industries, it serves as a fiber binder and surface improver, enhancing print quality and fabric durability (Kirby, 1986; Maher & Cremer, 1993).

4.5. Fresh Consumption and Colored Waxy Maize

In East and Southeast Asia, waxy maize is a primary vegetable consumed fresh during the milk stage (Harakotr et al., 2014). Yellow, white, purple, and black varieties exist, with purple and black forms containing high levels of anthocyanins (cyanidin-3-O-β-D-glucoside), which offer antioxidant, anti-diabetic, and anti-obesity benefits (Tsuda et al., 2003; Simla et al., 2016).

4.6. Global Demand and Market Dynamics

The global waxy maize starch market was valued at approximately USD 4.1–4.3 billion in 2024–2025, with a projected CAGR of 5.0–6.1%, potentially reaching USD 6.5–7.7 billion by 2033–2035 (Fact.MR, 2024). The Asia-Pacific and North American regions lead in consumption, driven by the food processing industry and the increasing demand for functional food and sports nutrition products.

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CHAPTER 2

THE CONTRIBUTION OF MEDICINAL AND AROMATIC PLANTS TO THE ECOLOGICAL AND AGRICULTURAL FUNCTIONS OF BEE PASTURES

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INTRODUCTION

Medicinal and aromatic plants play a significant role in conserving biodiversity and sustainably using natural resources because of the wide range of benefits they provide to ecosystems. In addition to supporting rural communities in terms of health and income, they promote environmentally friendly agricultural practices, thereby contributing to biodiversity management (Padulosi et al., 2002).

Phenolic compounds, which are among the main secondary metabolites found in these plants, play a role in defending them against ultraviolet radiation and attacks by pathogens, parasites, and predators. These compounds increase plant survival by creating resistance to environmental stress factors owing to their antioxidant properties. These mechanisms indirectly contribute to strengthening ecosystem health (Samarth et al., 2017).

This book chapter aims to address the contributions of medicinal and aromatic plants to the ecological and agricultural functions of bee pastures, within a multidimensional framework. It provides a scientific perspective on the sustainable management of bee pastures and habitats by evaluating plant diversity, pollinator-supporting habitat structure, resource continuity, the impact of climate change, and economic potential, with a specific focus on Turkish flora.

The importance of medicinal and aromatic plants in the flora of Turkey

Turkey's rich flora has great potential in terms of biodiversity, as well as being valuable economically, ecologically and scientifically. Shaped by its geographical and climatic diversity, the country's flora boasts a remarkable wealth of medicinal and aromatic plants. The country is home to over 11,000 flowering plant species, a significant proportion of which possess medicinal and aromatic properties, further emphasising the scientific and economic importance of this field. Plant families with pronounced aromatic properties, such as Lamiaceae, Asteraceae, and Apiaceae, as well as genera such as Sideritis, Salvia, and Thymus, are among the fundamental elements of this potential (Baser, 2002).

The rich variety of flowering plants in Turkey demonstrates that aromatic diversity is an important indicator of chemical diversity and provides valuable resources for taxonomic and ecological research (Baser, 2002; Dilbirligi & Yazgan, 2007).

Bee Pastures and Pollinator-Supporting Plant Diversity

Medicinal and aromatic plants play a significant role in maintaining biodiversity by supporting natural pollinators. Therefore, when planning bee pastures, flowering periods and quality of the floral resources provided should be among the key criteria for selecting species. Ratibida pinnata and Zizia aurea support bee nutrition, and the integration of these species into agricultural areas can increase bee diversity (Kordbacheh et al., 2020). Viburnum spp. provides attractive floral resources in urban landscapes (Mach and Potter, 2018), whereas Tripolium pannonicum and Limonium spp. are heavily visited by honey and wild bees in halophytic pastures (Davidson et al., 2020).

Local wildflower strips integrated into crop fields increase colony strength and pollinator diversity owing to the variety of flowers they offer (Kordbacheh et al., 2020).

Habitat Structure, Landscape Management and the Sustainability of Bee Populations

Habitat structural diversity is critical for bee population sustainability. The presence of flowering plants is as important as the availability of nesting and shelter areas, particularly for ground-nesting species (Murray et al., 2012).

Pressures arising from agricultural and urban activities must be considered, and regulations aimed at reducing human impact should be implemented (Stein et al., 2018). Protecting these habitats is crucial for population continuity, as bees require food sources, areas for reproduction, and places to rest (Lichtenberg et al., 2017).

The effect of pollen and nectar continuity on colony dynamics

The availability of pollen and nectar sources directly affects the growth, reproductive success, and productivity of bee colonies. Therefore, it is crucial that species flower throughout the year without any gaps. Studies on Bombus vosnesenskii have shown that early season abundance of resources supports colony development, with increased total offspring and male production. Seasonal resource continuity is a key determinant of colony growth (Malfi et al., 2019).

Increasing the availability of flowering plants in the agricultural landscape during the periods of colony establishment and reproduction is necessary (Westphal et al., 2009). Providing continuous resources throughout the year increases colony weight, enhances productivity, and reduces the energy expended on pollen collection. This is consistent with findings showing that sugar water and pollen supplements increase the reproductive success of Bombus colonies. The distribution and quality of resources within a landscape also play a decisive role in colony performance (Requier et al., 2020).

The agricultural and economic contributions of medicinal and aromatic plants

By-products such as essential oils, biocides, and cosmetics derived from these plants have high commercial value and economic potential. The high-quality pollen and nectar that these plants provide positively impact the quality and market value of bee products (Bulut, 2019; Güller & Çakar, 2020).

Therefore, medicinal and aromatic plants are of strategic importance, both ecologically and in terms of agricultural production and rural development.

Species Diversity, Climate Change and Adaptive Management Approaches

Increasing species diversity is a key factor in strengthening the resilience of ecosystems and bee colonies. High diversity increases functional resilience and compositional stability, providing a stronger capacity to adapt to environmental changes (Baert et al., 2016; Silva Pedro et al., 2014; Massa et al., 2013).

Climate change directly impacts plant–pollinator interactions by altering flowering times in many species and disrupting inter-species synchronisation (Chen et al., 2022; Satake et al., 2013). The sensitivity of flowering phenology to environmental factors significantly affects plant community structure and dynamics. Therefore, adaptive management approaches should be based on the regular monitoring of local species' flowering patterns, with decision-making processes based on these data. Incorporating local and traditional knowledge systems into adaptation strategies helps develop culturally relevant and sustainable solutions (Nyong et al., 2007; Locatelli et al., 2011; Zhang et al., 2019; Felton et al., 2024).

Result

The findings of this study clearly demonstrate the critical role of medicinal and aromatic plants in the ecological functionality and agricultural sustainability of bee pastures. These plants support the nutrition of bee colonies by providing pollen and nectar, strengthening habitat structure, increasing ecosystem resilience, and contributing to biodiversity conservation.

The growth, reproductive success, and long-term sustainability of bee colonies depend on species diversity and seasonal resource continuity. Integrating medicinal and aromatic plants into agricultural and urban landscapes is an effective way to create pollinator-friendly habitats for bees. This approach also enables the development of adaptive management strategies to mitigate the negative effects of climate change on flowering phenology in the future.

Turkey's rich flora offers significant potential for medicinal and aromatic plants. Addressing this potential holistically through bee pastures and pollinator management can increase both ecological and economic gains. Contributions to rural development through essential oils and other value-added products further reinforce the importance of these plants in agricultural landscapes.

Therefore, strategies for managing bee habitats, conserving biodiversity, and ensuring the sustainability of pollination services must focus on species diversity, resource continuity, and climate-change adaptation. In this context, medicinal and aromatic plants should be considered cornerstones of this approach.

Disclosure of AI usage

During the preparation of this work, the author utilised artificial intelligence for purposes such as generating text, checking grammar, analysing data and assisting with literature research. After using artificial intelligence, the authors reviewed and edited the content as necessary and take full responsibility for the published work.

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CHAPTER 3

THE CONCEPT OF BEE PASTURE IN THE CONTEXT OF MEDİCİNAL AND AROMATIC PLANTS AND THE FORAGING AREAS OF BEES

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INTRODUCTION

Using medicinal and aromatic plants in bee pastures supports the healthy development of bee populations by increasing biodiversity, owing to the rich sources of nectar and pollen they provide. This boosts bee productivity and improves the quantity and quality of beekeeping products, such as honey, pollen, and bee milk. Integrating these plants into beekeeping activities contributes to rural development (Decourtye et al., 2010).

Integrating medicinal and aromatic plants into bee pastures is strategically important for beekeeping and plant diversity planning because it promotes economic growth, local development, and ecosystem health. These plants maintain colony health by providing nectar and pollen throughout the year (Jones & Rader, 2022), strengthen the ecosystem by supporting pollinator diversity, and enable bee feeding owing to their different flower structures (Martins et al., 2017).

This study aimed to address the concept of bee pastures in the context of medicinal and aromatic plants, evaluate the ecological, agricultural, and economic dimensions of bee feeding areas, and provide a scientific framework for the sustainable planning of bee pastures.

The Concept of Bee Pasture and Its Spatial Scope

The vegetation within an average radius of 2 km around the beehives is defined as bee pasture. Although honey bees can forage up to 4–11.3 km away, they utilise the area within 600–800 m most effectively. This area does not have to consist solely of natural plants; cultivated crops are also an important food source for bees. If there are insufficient flowering plants within a 2 km radius of the bees, cultivating agricultural crops in this area during the necessary periods is known as an artificial bee pasture (Çaçan et al., 2020).

The Nutritional Requirements of Bees: The Role of Pollen and Nectar

The vegetation within an average radius of 2 km around the beehives is defined as bee pasture. Although honey bees can forage up to 4–11.3 km away, they utilise the area within 600–800 m most effectively. This area does not have to consist solely of natural plants; cultivated crops are also an important food source for bees. If there are insufficient flowering plants within a 2 km radius of the bees, cultivating agricultural crops in this area during the necessary periods is known as an artificial bee pasture (Çaçan et al., 2020).

The Nutritional Requirements of Bees: The Role of Pollen and Nectar

Pollen is the primary source of protein for honeybees and is critical for larval development and the health of adult bees. In monoculture and intensive farming areas, pollen diversity and abundance are particularly important for optimal nutrition (Topitzhofer et al., 2019). Bees adjust their foraging behaviour according to the nutritional value of the pollen and the reserves available within the colony, and they generally prefer pollen with a high protein content. In contrast, nectar is the main ingredient in honey production (Ghosh et al., 2020; Kitaoka & Nieh, 2008; Zhang et al., 2019). In summary, the diversity and continuity of pollen and nectar sources are crucial for the sustainability of bee colonies.

The Role of Medicinal and Aromatic Plants in Bee Nutrition

MAP (Medicinal and Aromatic Plants) creates valuable sources of nectar and pollen for bees, which supports their survival and reproductive success. This enhances the quality of honey and other bee products (Durazzo et al., 2021). The pollination services provided by bees contribute to local economies by increasing agricultural productivity (Prodanović et al., 2024). Consciously selecting plant species when planning bee pastures is critical because it increases bee diversity and supports the population density (Bendel et al., 2019; Thapa-Magar et al., 2020). Owing to these characteristics, TABs play a vital role in the ecological design of bee pastures.

Medicinal and aromatic plants are rich in diversity, providing valuable food sources that support bee populations and enhance the quality of bee products. Lavender (Lavandula spp.) is a valuable nectar source owing to its abundant flowering and aromatic properties. The aromatic oils in sage (Salvia spp.) flowers attract bees and improve the quality of bee products (Durazzo et al., 2021). Rosemary (Salvia rosmarinus) is another important species commonly used in bee pastures thanks to its evergreen nature and frequent flowering. Thyme (Thymus spp.) is another species frequently visited by bees, and mint (Mentha spp.) has the potential to be an important component of bee pastures because of its aromatic oils and abundant flowering (Durazzo et al., 2021).

Species Selection and Flowering Continuity in Bee Pasture Planning

When planning bee pastures, the aim should be to create a sustainable environment that supports biodiversity and meets the nutritional and habitat requirements of bees. Therefore, it is important to have a high level of floral richness and species diversity to provide a continuous source of flowers throughout the season, thus meeting the nutritional needs of bees at different times (Doublet et al., 2022).

Using a balanced combination of native and non-native plant species can increase pollinator diversity (Seitz et al., 2020), as native species may be more suitable for local bee populations. The selection of species that flower from spring to autumn ensures a continuous supply of nectar and pollen, preventing periods of starvation and supporting colony health (Doublet et al., 2022).

To ensure that pollinators have access to uninterrupted food sources throughout the year, it is necessary to consciously select species with different flowering periods. Flowering times that follow each other without gaps create a sustainable feeding cycle for the bees. In this context, linden species (Tilia spp.) are an important source of pollen and nectar for both honey and wild bees, providing an intense supply in June and July (Dmitruk et al., 2024). Wild plants in agricultural areas also provide pollinators with a continuous food supply throughout the season, owing to the early flowering of winter annuals and later flowering of summer annuals and perennials (Milberg et al., 2024).

Land Use, Climate Change and Botanical Diversity

Medicinal and aromatic plants are critical for maintaining pollinator diversity and preserving ecosystem function. Therefore, they are a priority for biodiversity conservation (Kougioumoutzis et al., 2024).

Botanical diversity directly affects bee health; different flower structures and nutrient contents enable bees to feed in a wider ecological niche (Casanelles-Abella et al., 2022; Hausmann et al., 2015). Urban areas can potentially offer rich plant diversity; however, this advantage diminishes when floral resources are not protected (Rahimi et al., 2022).

The Economic and Rural Development Dimension of Medicinal and Aromatic Plants

From an economic perspective, cultivating medicinal and aromatic plants enhances the quality of beekeeping products and has the potential to promote rural development by providing farmers with an additional source of income from the production of high-value goods, such as medicinal products and essential oils (Bulut, 2020).

Medicinal and aromatic plants are also invaluable from historical and social perspectives. They constitute an important part of biodiversity, and their conservation is necessary for the sustainability of these resources (Acıbuca & Budak, 2018).

Result

This study demonstrates that medicinal and aromatic plants are critical for the functionality of bee pastures. The presence of such pastures, along with diverse and continuous pollen and nectar sources, has a direct impact on the health and sustainability of bee colonies when plant species are consciously selected for. In addition to meeting the nutritional requirements of bees, medicinal and aromatic plants enhance the quality of bee products and contribute to agricultural productivity and local economies through pollination services.

In line with these findings, medicinal and aromatic plants that flower continuously throughout the season, are adapted to local conditions, and have high species diversity should be prioritised in bee pasture planning. Integrating medicinal and aromatic plants into agricultural, semi-natural, and urban areas will contribute to the conservation of pollinator diversity and enhance ecosystem functionality. Furthermore, the sustainable management and conservation of these plants should be prioritised to ensure the long-term continuity of beekeeping activities and rural development.

Disclosure of AI usage

During the preparation of this work, the author utilised artificial intelligence for purposes such as generating text, checking grammar, analysing data and assisting with literature research. After using artificial intelligence, the authors reviewed and edited the content as necessary and take full responsibility for the published work.

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CHAPTER 4

EVALUATION FOR THE LAST TEN YEARS (2015-2024) AND NEXT YEARS (2025-2030) OF CHANGES IN AGRICULTURAL MECHANIZATION LEVEL OF BİNGÖL PROVINCE

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INTRODUCTION

Agricultural mechanization is considered a fundamental element that increases labor productivity, reduces production costs, and ensures the timely and efficient execution of agricultural activities through the use of machinery, equipment, and automation systems in production processes. The development of agricultural mechanization is not limited to increasing the quantity of agricultural production; it also has direct impacts on product quality, resource use efficiency, environmental sustainability, and producer welfare. In regions with low levels of mechanization, the reliance on human and animal power for production activities is a significant factor limiting agricultural productivity. In this context, mechanization is a strategic tool for the modernization and increased competitiveness of the agricultural sector.

However, for agricultural mechanization to be planned effectively and made sustainable, it is necessary to analyze the current situation as well as predict future trends. At this point, agricultural mechanization projections emerge as an important planning tool guiding the long-term development of the agricultural sector. Mechanization projections allow for the estimation of future values in terms of changes in the number of agricultural machines, power density, mechanization level, and machine usage rates. These predictions play a critical role in the formulation of agricultural policies, guiding investment decisions, and determining regional development strategies.

Bingöl province is one of the provinces in the Eastern Anatolia Region with an economy focused on agriculture and livestock farming. The local production structure, which has developed under the determining influence of geographical and climatic conditions, means that a large portion of the region's population earns its livelihood from agriculture and livestock farming. These sectors increase rural employment in the province and are considered a fundamental priority in terms of the sustainability of agricultural production systems. Due to Bingöl's topographical structure, arable land is limited, and plains and valleys are heavily used for agriculture. In this context, modern crop production techniques and technologies have not yet become widespread; the availability of agricultural tools, equipment, and tractors is below the regional average.

This study calculated the numerical change in agricultural machinery in Bingöl province over the past 10 years and projected the province's agricultural machinery inventory for the year 2030.

MATERIAL AND METHOD

Bingöl Province is located in the Upper Euphrates section of the Eastern Anatolia Region. It is bordered by Muş to the east, Erzurum and Erzincan to the north, Tunceli and Elazığ to the west, and Diyarbakır to the south. Bingöl Province lies between 41º 20´- 39º 56´ east longitudes and 39º 31´-36º 28´ north latitudes (Aral et. al, 2023; Anonymous, 2025a). Of its total surface area of 8253 km2, 32.10% is forest, 17.67% is agricultural land, 30.31% is pasture, 0.70% is fallow land, and 19.22% consists of other areas (Anonymous, 2024). In terms of climate and vegetation, it has the characteristics of a transitional region between the East and Southeast (Anonymous, 2025b). The most widespread vegetation type in Bingöl province is scrubland (48.8%). This is followed by steppe areas with 39% and broadleaf forest areas with 11.2%. The least common vegetation types are mixed forests (0.9%) and coniferous forests (0.1%) (Avci et al., 2018) (Figure 1).

Figure 1. Bingöl province map

According to 2024 data, 127745 hectares of land in the province was allocated to grains and other plant products, while 5316 hectares were allocated to fallow land. According to 2024 data, the most cultivated crops in the province are shown in Table 1 (Anonymous, 2025c).

Table 1. Agricultural production quantities of major crops in Bingöl province

Crop	Production quantities (tons)
Meadow hay	2555926
Alfalfa	378364
Maize	124278
Wheat	21458
Barley	4325
Sainfoin	4068
Hungarian vetch	3686

The material of the study consisted of the agricultural machinery data of the Turkish Statistical Institute for the years 2015-2024 for the province of Bingöl (Anonymous 2025d). This data is used to determine the percentage ratios, either an increase or a decrease, for every agricultural tools and machinery by analyzing the covering years. After that, taking into account the 10-year usage amounts of agricultural machines, the percentage rates of increase and decrease in their numbers were calculated, and the average coefficients of these percentage rates were determined. By using the coefficients determined based on the data of previous years, the projections of agricultural tools and machines widely used in Bingöl until 2030 are calculated using the same method in cited studies (Baran et al., 2019; Baran and Kaya, 2021; Ertop et al., 2021; Gül et al., 2023; Şin et al, 2023; Turgut, 2023a; Turgut, 2023b; Turgut, 2025).

RESULTS AND DISCUSSIONS

In the land use assessment conducted in Bingöl province, it was determined that 11.11% of water erosion occurs in agricultural lands and 83.24% occurs in pasture lands. The total erosion amount in agricultural lands and pasture lands in Bingöl province is 6814160.4 tones year-1 (Anonymous, 2020). Therefore, it is important to adopt conservation soil tillage methods throughout the province. As seen in Table 2, the highest projection coefficient with positive percent of 35.09 value is occurred in case of toothed harrow among those taken into consideration. Disc harrow, subsoiler, cultivator, arc opening plow, moldboard type tractor plough, rotary cultivator, stubble plough (moldboard type), disc type tractor plough, land roller are followed rotary tiller with positive projection coefficient value of 25.54%, 14.71%, 13.33%, 13.21%, 9.18%, 4.75%, 4.34%, 4.15%, 2.22% respectively. Animal drawn plough has negative projection coefficient with a percent of 5.59.

Table 2. Projection of Some Soil Tillage Tools and Machines Widely Used in Bingöl Province

Years	Mouldboard type tractor plough	Stubble plough (moldboard type)	Disc type tractor plough	Animal drawn plough	Arc Opening Plow	Cultivator	Disc harrow	Toothed harrow	Rotary cultivator	Subsoiler	Land roller
2015	561	22	48	267	20	430	22	148	518	19	87
2016	563	22	50	259	22	435	26	149	583	19	87
2017	887	20	69	224	36	804	70	594	592	29	81
2018	891	20	70	215	36	812	80	598	602	30	85
2019	943	20	54	213	46	867	74	650	602	50	93
2020	971	26	53	214	53	922	67	657	712	51	94
2021	985	27	51	213	58	932	72	687	723	51	94
2022	1004	29	53	206	67	965	85	685	745	52	102
2023	1023	31	55	198	70	982	87	688	757	53	103
2024	1127	31	63	155	51	1114	102	697	776	55	105
Years	**Percentage Change**										
2015-2016	0.36	0.00	4.17	-3.00	10.00	1.16	18.18	0.68	12.55	0.00	0.00
2016-2017	57.55	-9.09	38.00	-13.51	63.64	84.83	169.23	298.66	1.54	52.63	-6.90
2017-2018	0.45	0.00	1.45	-4.02	0.00	1.00	14.29	0.67	1.69	3.45	4.94
2018-2019	5.84	0.00	-22.86	-0.93	27.78	6.77	-7.50	8.70	0.00	66.67	9.41
2019-2020	2.97	30.00	-1.85	0.47	15.22	6.34	-9.46	1.08	18.27	2.00	1.08
2020-2021	1.44	3.85	-3.77	-0.47	9.43	1.08	7.46	4.57	1.54	0.00	0.00
2021-2022	1.93	7.41	3.92	-3.29	15.52	3.54	18.06	-0.29	3.04	1.96	8.51
2022-2023	1.89	6.90	3.77	-3.88	4.48	1.76	2.35	0.44	1.61	1.92	0.98
2023-2024	10.17	0.00	14.55	-21.72	-27.14	13.44	17.24	1.31	2.51	3.77	1.94
Projection Coefficient	**9.18**	**4.34**	**4.15**	**-5.59**	**13.21**	**13.33**	**25.54**	**35.09**	**4.75**	**14.71**	**2.22**
Years	**Projections**										
2025	1137	30	65	157	58	1262	128	942	813	63	107
2026	1146	30	66	159	65	1431	161	1272	851	72	110
2027	1156	29	68	161	74	1621	202	1718	892	83	112
2028	1166	29	70	163	84	1837	253	2321	934	95	115
2029	1176	28	72	165	85	2082	318	3136	979	109	117
2030	1186	28	74	167	86	2360	399	4236	1025	125	120

As seen in Table 3, the highest projection coefficient with positive percent of 31.68 value is occurred in case of manure spreading machinery among those taken into consideration. The agricultural soils of Bingöl province, like those throughout our country, are poor in organic matter (Taş and Demir; 2022). Although animal husbandry is intensive throughout the province, animal manure is not fully utilized. However, the increase in the number of manure spreading machinery shows that there is positive progress in this regard. Chemical fertilizer spreader, pneumatic precision drill, tractor-drawn seed drill, stubble drill, combined seed drill and universal seed drill, are followed manure spreading machinery with positive projection coefficient value of 29.74%, 19.63%, 13.75%, 10.76%, 9.89%, 2.22% respectively. In the 2030 projection, it is predicted that the largest number of chemical fertilizer spreader will be in the province.

Table 3. Projection of Some Sowing-Planting Fertilizer Machines Widely Used in Bingöl Province

Years	**Tractor-drawn seed drill**	**Combined seed drill**	**Pneumatic precision drill**	**Stubble drill**	**Universal seed drill**	**Manure spreading machinery**	**Chemical Fertilizer Spreader**
2015	10	26	5	18	5	6	19
2016	10	28	5	23	5	6	20
2017	11	28	2	22	5	8	23
2018	11	28	3	26	5	8	24
2019	11	30	3	27	5	8	25
2020	15	33	6	31	5	8	28
2021	17	35	6	40	5	27	80
2022	18	45	6	43	5	29	91
2023	23	48	10	43	5	29	111
2024	30	59	12	43	6	31	117
Years				**Percentage Change**			
2015-2016	0.00	7.69	0.00	27.78	0.00	0.00	5.26
2016-2017	10.00	0.00	-60.00	-4.35	0.00	33.33	15.00
2017-201	0.00	0.00	50.00	18.18	0.00	0.00	4.35
2018-2019	0.00	7.14	0.00	3.85	0.00	0.00	4.17
2019-2020	36.36	10.00	100.00	14.81	0.00	0.00	12.00

2020-2021	13.33	6.06	0.00	29.03	0.00	237.50	185.71
2021-2022	5.88	28.57	0.00	7.50	0.00	7.41	13.75
2022-2023	27.78	6.67	66.67	0.00	0.00	0.00	21.98
2023-2024	30.43	22.92	20.00	0.00	20.00	6.90	5.41
Projection Coefficient	**13.75**	**9.89**	**19.63**	**10.76**	**2.22**	**31.68**	**29.74**
Years				**Projections**			
2025	34	65	14	48	6	41	152
2026	39	71	17	53	6	54	197
2027	44	78	21	58	6	71	255
2028	50	86	25	65	7	93	331
2029	57	95	29	72	7	123	430
2030	65	104	35	79	7	162	558

Horticulture, especially apple cultivation, holds a significant place in Bingöl province. Apples, walnuts, pears, mulberry, plum, strawberry and apricot are grown in significant amounts (Anonymous, 2025e). Especially knapsack sprayer is widely used in these areas. It is seen that knapsack sprayers are appearing to be the most abundant. On the other hand, it is seen that barrow duster and combine sprayer (28.92%) increased more than these. Engine driven sprayers (13.10%) and atomizers (0.97%) have become the most commonly used machines in horticulture after these two. And also PTO driven sprayers (54.23%) are followed by barrow duster and combine sprayer with positive percentage coefficient value of 28.92% (Table 4).

Table 4. Projection of Spraying Machines Widely Used in Bingöl Province

Years	Knapsack sprayer	Barrow duster and combine sprayer	PTO driven sprayer	Engine driven sprayer	Atomizer
2015	245	4	2	33	59
2016	249	4	2	34	60
2017	467	5	2	62	60
2018	468	15	2	64	60
2019	492	16	2	63	60
2020	507	16	2	61	63

2021	526	18	2	66	66
2022	545	19	7	67	68
2023	628	19	21	71	63
2024	923	21	29	84	64
Years	**Percentage Change**				
2015-2016	1.63	0.00	0.00	3.03	1.69
2016-2017	87.55	25.00	0.00	82.35	0.00
2017-201	0.21	200.00	0.00	3.23	0.00
2018-2019	5.13	6.67	0.00	-1.56	0.00
2019-2020	3.05	0.00	0.00	-3.17	5.00
2020-2021	3.75	12.50	0.00	8.20	4.76
2021-2022	3.61	5.56	250.00	1.52	3.03
2022-2023	15.23	0.00	200.00	5.97	-7.35
2023-2024	46.97	10.53	38.10	18.31	1.59
Projection Coefficient	**18.57**	**28.92**	**54.23**	**13.10**	**0.97**
Years	**Projections**				
2025	1094	27	45	95	65
2026	1298	35	69	107	65
2027	1539	45	106	122	66
2028	1824	58	164	137	67
2029	2163	75	253	155	67
2030	2565	96	390	176	68

Harvesting machines commonly used in Bingöl province are given in Table 5. It can be observed that a high positive projection coefficient of 62.78% for the straw conveyor and unloader. The straw conveyor and unloaders are followed by the forage harvester, baler, tractor drawn mover, straw machine, corn forage harvester, thresher with positive projection coefficient value of 47.15%, 23.74%, 14.21%, 12.16%, 4.03%, 3.17% respectively. Hay rake has negative projection coefficient with a percent of 5.39. Since livestock farming plays a significant role in the region, there is a high concentration of machinery specifically designed for roughage application.

Table 5. Projection of Harvest-Threshing Machines Widely Used in Bingöl Province

Years	Thresher	Hay rake	Straw conveyor and unloader	Straw machine	Corn forage harvester	Baler	Tractor drawn mower	Forage harvester
2015	240	25517	1	40	20	21	160	11
2016	240	25515	1	40	22	23	162	12
2017	294	24276	1	56	23	34	184	62
2018	299	24408	1	59	24	39	190	63
2019	319	24341	1	64	26	50	232	64
2020	252	24488	5	69	28	55	371	65
2021	254	24505	5	78	30	61	383	61
2022	258	18020	5	83	26	91	417	61
2023	265	18122	12	99	27	123	456	61
2024	301	14743	15	108	28	133	485	61
Years	**Percentage Change**							
2015-2016	0.00	-0.01	0.00	0.00	10.00	9.52	1.25	9.09
2016-2017	22.50	-4.86	0.00	40.00	4.55	47.83	13.58	416.67
2017-2018	1.70	0.54	0.00	5.36	4.35	14.71	3.26	1.61
2018-2019	6.69	-0.27	0.00	8.47	8.33	28.21	22.11	1.59
2019-2020	-21.00	0.60	400.00	7.81	7.69	10.00	59.91	1.56
2020-2021	0.79	0.07	0.00	13.04	7.14	10.91	3.23	-6.15
2021-2022	1.57	-26.46	0.00	6.41	-13.33	49.18	8.88	0.00
2022-2023	2.71	0.57	140.00	19.28	3.85	35.16	9.35	0.00
2023-2024	13.58	-18.65	25.00	9.09	3.70	8.13	6.36	0.00
Projection Coefficient	**3.17**	**-5.39**	**62.78**	**12.16**	**4.03**	**23.74**	**14.21**	**47.15**
Years	**Projections**							
2025	311	13949	24	121	29	165	554	90
2026	320	13198	40	136	30	204	633	132
2027	331	12487	65	152	32	252	723	194
2028	341	11815	105	171	33	312	825	286
2029	352	11179	171	192	34	386	943	421
2030	363	10577	279	215	35	477	1077	619

The 2030 projection estimates that the number of feed grinders in the province will reach 272, and the number of feed spreading trailers will reach 38 (Table 6).

Table 6. Projection of Feed Mechanization Machines Widely Used in Bingöl Province

Years	Feed grinder	Feed spreading trailer
2015	8	7
2016	8	8
2017	9	8
2018	15	9
2019	16	11
2020	19	12
2021	27	13
2022	40	13
2023	42	15
2024	55	18
Years	**Percentage Change**	
2015-2016	0.00	14.29
2016-2017	12.50	0.00
2017-2018	66.67	12.50
2018-2019	6.67	22.22
2019-2020	18.75	9.09
2020-2021	42.11	8.33
2021-2022	48.15	0.00
2022-2023	5.00	15.38
2023-2024	30.95	20.00
Projection Coefficient	25.64	11.31
Years	**Projection**	
2024	69	20
2025	87	22
2026	109	25
2027	137	28
2028	172	31
2029	216	34
2030	272	38

Significant investments have been made in the dairy industry in Bingöl province. These developments have encouraged the local population, and private investments have begun to increase. Many entrepreneurs, particularly with the help of government support provided in 2020-2021, have established milking facilities of various capacities. These initiatives have also contributed to employment in the region. However, the SÜTAŞ East-Southeast Anatolia Dairy Project Bingöl Integrated Facilities, which started operating in the province in 2021, has increased interest in dairy farming throughout the province. If full-capacity production is achieved, it is projected that out of a daily milk production of 911000 liters, 212500 liters will come from SÜTAŞ farms, and the remaining 698500 liters will be sourced from regional producers (Anonymous, 2025f). It is expected that the number of milking facilities in the province will be at least 42 by 2030, and the number of mobile milking machines will be 18587. Considering that one of the factors that increases milk yield is the use of mechanization in milking, increasing the use of mechanization plays a significant role in increasing milk production in animals and profitability in dairy farms (Metin Kıyıcı, 2018). A churn is a traditional milk processing tool used in Anatolia for the production of buttermilk and butter. Even with the projection of 2030, it can be predicted that traditional churning will not be abandoned, despite the development of technologically advanced churning machines (Table 7).

Table 7. Projection of Dairy Industry Machines Widely Used in Bingöl Province

Years	Milking facility	Milking machine (mobile)	Churn
2015	34	183	1886
2016	34	198	1886
2017	39	478	3242
2018	31	488	3153
2019	32	615	3292
2020	37	645	4277
2021	39	928	4294
2022	37	1386	4583
2023	39	1811	4440
2024	42	2147	4675
Years	**Percentage Change**		
2015-2016	0.00	8.20	0.00
2016-2017	14.71	141.41	71.90

2017-2018	-20.51	2.09	-2.75
2018-2019	3.23	26.02	4.41
2019-2020	15.63	4.88	29.92
2020-2021	5.41	43.88	0.40
2021-2022	-5.13	49.35	6.73
2022-2023	5.41	30.66	-3.12
2023-2024	7.69	18.55	5.29
Projection Coefficient	**2.94**	**36.12**	**12.53**
Years	**Projection**		
2024	43	2922	5261
2025	45	3978	5920
2026	46	5415	6662
2027	47	7370	7497
2028	49	10032	8436
2029	50	13655	9493
2030	51	18587	10683

CONCLUSIONS

This study evaluates the level of agricultural mechanization in Bingöl province based on current indicators and presents future mechanization projections. The findings show that agricultural mechanization in Bingöl province is generally below the Turkish average, and a significant portion of agricultural activities are still carried out with low machinery intensity. In particular, key mechanization indicators such as agricultural land per tractor, machinery power per unit area, and variety of agricultural machinery reveal that the province's current production structure has a limited level of mechanization.

The geographical structure of the province, the fragmented and sloping nature of agricultural areas, and the small and scattered nature of farms are among the main factors limiting the widespread adoption of mechanization. Furthermore, the fact that agricultural production is largely based on livestock farming and that fodder crops dominate plant production leads to a limited range of machinery and equipment. This situation highlights the importance of using functional equipment suitable for the production pattern, rather than simply increasing mechanization quantitatively. Particularly for small-scale businesses, the widespread adoption of shared machinery, machinery parks, and cooperative-based mechanization models are considered important tools that can increase the effectiveness of mechanization investments.

Increasing the level of agricultural mechanization in Bingöl province will not only be possible by increasing the number of agricultural machines, but also by adopting a sustainable, economical, and environmentally friendly mechanization approach based on scientific projections. This approach will make significant contributions to increasing the agricultural productivity of the province and achieving rural development goals.

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CHAPTER 5

DESIGN-ORIENTED EVALUATION OF THERMOPLASTIC MATERIALS USED IN AGRICULTURAL MACHINERY SYSTEMS

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INTRODUCTION

Agricultural production systems are undergoing a rapid transformation process towards higher productivity and lower resource consumption in line with the effects of climate change, rising input costs, environmental constraints, and sustainability goals. This transformation highlights not only the functional adequacy of agricultural machinery but also engineering performance indicators such as mass-stiffness ratio, vibration behaviour, chemical and environmental resistance, service life under impact and fatigue, and maintenance and operating costs. Agricultural machinery operates in open field conditions, exposed to variable temperature-humidity cycles, UV radiation, soil-borne particles, and aggressive chemical inputs such as fertilisers and pesticides. Therefore, the long-term behaviour of the materials used is critically important in terms of design.

In the field of agricultural machinery systems, there has been an increasing utilisation of thermoplastic polymers. The primary reasons for this can be attributed to the fact that these polymers possess a low density, exhibit inherent resistance to corrosion, and possess a capacity for vibration damping. Additionally, these materials possess the capability to produce complex geometries in a manner that is both economical and reproducible, a feat that can be accomplished through a variety of production technologies (Fartash Naeimi et al., 2025). The applications of thermoplastics in the domain of agricultural machinery are manifold and encompass a wide range of components, including fluid storage tanks, housing and bodywork elements, hose and pipe systems, guides, slides, bushings, gears, and load-bearing semi-structural components. This diversity serves to underscore the significance of thermoplastics not only in aesthetic or secondary applications, but also in components that are directly functional and critical to engineering.

Thermoplastic materials exhibit a wide range of mechanical and physicochemical properties due to their molecular chain structures, crystallisation degrees, and additive systems. The differences between semi-crystalline and amorphous structures are decisive for properties such as elastic modulus, impact strength, friction-wear behaviour, and chemical resistance. The utilisation of engineering thermoplastics, most notably polyamide (PA), polyacetal (POM), and ultra-high molecular weight polyethylene (UHMWPE), has the potential to provide alternative or complementary solutions to metal-based components in scenarios where friction and wear are of paramount importance. Such scenarios include bushings, bearing elements, gear systems, and guide surfaces (Tong et al., 2006; Walczak & Caban, 2021). However, the inherent limitations of thermoplastics, including the loss of rigidity with increasing temperature, creep under long-term load and ageing due to environmental conditions, necessitate the utilisation of an engineering approach in the evaluation of these materials for agricultural machinery design, with the focus being on service conditions.

Advances in polymer science and production technologies have resulted in a greater utilisation of thermoplastics in agricultural machinery applications, both in their pure form and in modified forms with glass fibre, mineral fillers, or functional additives. Reinforced thermoplastic systems can offer adequate mechanical performance with a reduced specific weight compared to metal-based materials. They also provide advantages such as corrosion resistance, vibration damping, and design freedom (Fajdek-Bieda & Wróblewska, 2024; Fartash Naeimi et al., 2025; Faruk et al., 2012; Salim et al., 2025). Nevertheless, novel design parameters, including production method, fibre orientation, microstructure-induced anisotropy, and stress concentrations in connection areas, are also emerging in such systems. This necessitates the consideration of material selection within the framework of the production method-geometry-microstructure-performance relationship (Mejia et al., 2021).

Nonetheless, a pivotal consideration in the utilisation of thermoplastic polymers within agricultural machinery systems pertains to their long-term behaviour. Under environmental influences such as UV radiation, temperature fluctuations, humidity, and chemical exposure, time-dependent damage mechanisms, including oxidative ageing, chain scission, creep, and fatigue, can occur in thermoplastics. These effects can result in a decline of mechanical properties, sealing and alignment problems, and ultimately a curtailed service life, particularly in load-bearing components or those requiring dimensional stability (Celina, 2013; Mao et al., 2021). Consequently, the performance of thermoplastics in agricultural machinery applications should be evaluated not solely based on their initial properties but also on their long-term behaviour, which represents real service conditions.

The objective of this study is to comprehensively address the use of thermoplastic materials in agricultural machinery systems. To this end, a systematic classification is provided, and their mechanical and environmental behaviour is analysed. Furthermore, service-condition-based material selection criteria are established.

1. ADVANTAGES AND LIMITATIONS OF THERMOPLASTICS IN AGRICULTURAL MACHINERY SYSTEMS

In the domain of agricultural machinery systems, thermoplastics are the preferred material due to their advantageous properties, including low density (which results in weight reduction), resistance to corrosion and chemicals, economical production of complex geometries, vibration damping, noise reduction, and manageable wear and friction performance, provided that the formulation is appropriate (Lewicka et al., 2024). However, the most critical characteristics of these materials are their pronounced viscoelastic behaviour (i.e. their ability to change shape under stress), greater sensitivity to temperature, and the risk of oxidative ageing (chemical degradation) and embrittlement (e.g. increased susceptibility to breakage) under UV exposure in some grades. It has been demonstrated that the mechanical behaviour of agricultural machinery systems equipped with thermoplastic materials may change due to chain breaks and oxidation formation in polyolefins under the interaction of UV, heat and oxygen, depending on external environmental conditions (Rodriguez et al., 2020).

2. ENGINEERING CRITERIA GOVERNING THE SELECTION OF THERMOPLASTICS IN AGRICULTURAL MACHINERY

The categorisation of thermoplastic polymers as either general-purpose or engineering thermoplastics does not merely reflect commercial or terminological distinctions; it signifies an engineering approach predicated on service conditions, loading regime, and long-term performance expectations. The pivotal criteria determining this categorisation are performance parameters such as elastic modulus, continuous service temperature, creep behaviour under long-term loading, dimensional stability, friction-wear resistance, and resistance to environmental effects.

As demonstrated in Table 1, general-purpose thermoplastics (e.g. polyethylene and polypropylene) are well-suited to applications involving low to medium mechanical loads, exhibiting wide tolerance ranges and minimal temperature sensitivity. These materials are particularly favoured in components such as storage bodies, housing elements, and fluid transport systems due to their cost-effectiveness, chemical resistance, and ease of production. In contrast, engineering thermoplastics (e.g. polyamide, polyacetal, and ultra-high molecular weight polyethylene) are materials developed for applications involving higher mechanical loads, friction and wear effects, precise tolerance requirements, and long service life expectations. Thanks to their more controlled creep and fatigue behaviour and high dimensional stability, these types of thermoplastics can offer alternative or complementary solutions to metal-based components in bearings, gear systems, guide surfaces, and load-bearing semi-structural parts.

Table 1. Evaluation criteria distinguishing general-purpose and engineering thermoplastics used in agricultural machinery systems

Evaluation criterion	General-purpose thermoplastics (PE, PP)	Engineering thermoplastics (PA, POM, etc.)
Elastic modulus	Low - medium	Medium - high
Continuous service temperature	Low	Medium - high
Long-term creep tendency	High	More controlled
Dimensional stability	Limited	High
Friction-wear resistance	Low to medium	High
Tolerance requirement	Wide tolerances	Tight tolerances
Environmental resistance	High chemical resistance, temperature sensitive	Balanced chemical and mechanical resistance
Agricultural machinery systems	Tank, cover, housing, hose	Bushings, gears, slides, guide surfaces
Predominant risk in design	Geometry and temperature	Load, time and friction

In this context, the selection of thermoplastic materials in agricultural machinery design should be approached not only based on initial mechanical properties but also through an engineering perspective that evaluates the interaction between load, time, and environment. The boundary between general-purpose and engineering thermoplastics should be determined according to application-specific performance requirements.

2.1. Polyethylene (PE: LDPE-LLDPE-HDPE-UHMWPE)

Polyethylene (PE) materials represent one of the most widely utilised thermoplastic groups within the agricultural sector. These materials can be categorised into four distinct types: LDPE (Low Density PE), LLDPE (Linear Low Density PE), HDPE (High Density PE), and UHMWPE (Ultra High Molecular Weight PE). Among these types, HDPE and UHMWPE have garnered particular attention in the context of their application in agricultural machinery systems, due to their inherent properties of durability and resistance to wear and tear. The primary areas of application for these PE materials encompass components that necessitate both storage stability and enhanced resistance to mechanical stress and abrasion.

1. **Storage components/tanks:** The utilisation of HDPE is particularly favoured in the fabrication of hollow and large-volume components. These thermoplastic materials are conducive to the production of one-piece, seamless tanks, which renders them well-suited for components that are exposed to chemical effects, such as sprayer tanks (Ortega et al., 2024).

2. **Wear-resistant parts:** The low friction coefficient, high wear resistance and good impact toughness of UHMWPE are key factors in its extensive utilisation in agricultural machinery systems, particularly in sliding slides, wear plates, chain guides and areas where continuous material flow occurs. However, the tribological performance of UHMWPE is contingent on the properties of the counter surface it contacts, the contact pressure and sliding speed, the operating temperature, and the presence of abrasive particles in the environment. Consequently, it is recommended that designs incorporating UHMWPE be evaluated using tribological tests that represent the actual operating conditions of the material and reflect field conditions (Tong et al., 2006).

From an engineering perspective, creep behaviour in semi-crystalline thermoplastics such as PE and HDPE must be considered a critical parameter in the design of agricultural machinery. Particularly in HDPE, as the operating temperature increases, the material's resistance to creep decreases and the time-dependent deformation rate increases significantly. This situation necessitates considering not only instantaneous stress levels but also the load-time-temperature- e interaction in applications where parts such as sprayer tanks, brackets, carrier covers, and similar components operate under long-term loads. In this context, the literature has shown that modelling approaches aimed at predicting long-term creep behaviour using short-term mechanical test results can be used as an effective tool, particularly in the early stages of design, for preliminary sizing and determining the safety factor (Amjadi & Fatemi, 2021; Mao et al., 2021).

2.2. Polypropylene (PP) and glass fibre reinforced (GF/PP) thermoplastics

Polypropylene (PP) is a thermoplastic with a low density, cost advantage, sufficient resistance to chemicals, and ease of shaping that is widely used in agricultural machinery. In this context, PP is frequently preferred for covers, housings, body elements, fan channels, bodywork parts, and protective boxes for electrical and electronic components. However, as the mechanical strength and rigidity of pure polypropylene can be limited for some applications, reinforcing PP often makes it more reliable for engineering applications. In glass fibre-reinforced PP (GF/PP) systems developed for this purpose, glass fibres are added to the PP matrix in specific proportions, significantly increasing the material's elastic modulus, load-bearing capacity and fatigue resistance. The glass fibres provide rigidity by carrying a large portion of the load, while the PP matrix maintains impact toughness, chemical resistance, and manufacturability. As a result, GF/PP materials offer higher mechanical performance compared to pure PP, making them suitable for use in semi-structural agricultural machinery components (Tucci et al., 2023).

In systems equipped with a long fibre thermoplastic (LFT) structure, the incorporation of glass fibre or analogous fibres in greater lengths leads to enhanced impact resistance and damage tolerance of the structure. Polypropylene-based LFTs, a category of composite, are manufactured in the form of large-sized protective elements and body components subject to vibration in agricultural machinery. Nevertheless, the dependable adaptation of GF/PP and LFT systems to agricultural machinery is contingent not solely on the material type utilised, but also on critical parameters inherent to the production process.

The distribution of glass fibres within the part, the processes applied during moulding by injection or compression, and the location of welded areas on the part significantly affect the material's impact resistance and fatigue performance. Consequently, an exclusive reliance on a single mechanical property, such as tensile strength, in the selection of materials may result in undesirable outcomes, including breakage and service life concerns, when subjected to actual field conditions (Ragupathi & Balle, 2024).

2.3. Polyamide (PA)-based thermoplastics (PA6 and PA66) and tribological applications

PA6 and PA66 are two fundamental thermoplastics that are frequently utilised in engineering applications within the polyamide (nylon) group. PA66 typically exhibits a higher melting temperature, superior temperature resistance, and greater rigidity in comparison to PA6. Both polyamide types are highly prevalent in agricultural machinery systems for applications such as bushings, sliding bearings, rollers, guide elements, and gear-like moving parts, due to their relatively high strength, effective wear resistance, and suitable tribological properties. In such components, polyamides have been shown to offer certain advantages over metal parts, including quieter operation, lower maintenance requirements, and the ability to operate without lubrication under certain conditions. However, the most critical property of PA6 and PA66 that must be carefully considered in engineering design is their tendency to absorb water and moisture. Polyamides have been observed to absorb moisture from the environment, which can cause dimensional changes (swelling) in the material. The absorption of moisture has been shown to have a detrimental effect on part tolerances, resulting in reduced clearances, increased friction and, consequently, higher temperatures, particularly in bushing and bearing applications. Furthermore, the presence of moisture has been observed to induce a plasticising effect in polyamides, thereby rendering the material more ductile whilst concomitantly reducing the modulus of elasticity and certain mechanical strength values. In the design of agricultural machinery, it is insufficient to base PA-based parts solely on material properties under "dry" conditions; the part's dry and humid operating conditions and temperature effects must be evaluated together. In practice, this approach means that design clearances, tolerances, and contact surfaces must be controlled according to the most unfavourable humidity-temperature combination (Pieniak et al., 2023).

The operating conditions of PA-based bushings and sliding bearings in agricultural machinery frequently deviate considerably from the ideal conditions defined in laboratory environments. In the field, contaminants such as soil, sand, fertiliser granules, and plant residues enter the friction zone, thereby shifting the system from classical two-surface friction to a wear regime. Furthermore, lubrication in agricultural machinery is often discontinuous; lubrication intervals may be extended, or oil films may be disrupted by contaminants. Under these conditions, the performance of polymer bushings is determined not only by the material type but also by load, speed, temperature, and ambient humidity. Although this approach provides a practical design criterion for evaluating the heat generated and wear tendency in sliding bearings, it is not sufficient on its own in agricultural applications. It has been demonstrated that the presence of abrasive particles, in conjunction with elevated temperatures, has the potential to result in the premature failure of components under field conditions, thereby exceeding the limits specified in catalogues. Consequently, when selecting a PA6 or PA66-based bushing or bearing element, it is advisable to refrain from relying exclusively on catalogue data. Instead, the efficacy of the design can be ascertained through the implementation of wear tests that encompass dusty environments and irregular lubrication scenarios, which are considered to represent real-field conditions. This approach has been shown to yield more favourable outcomes with respect to design reliability and service life (Walczak & Caban, 2021).

2.4. Tribological behaviour and the effect of temperature in polyoxymethylene (POM) materials

POM (polyoxymethylene) is a frequently preferred engineering thermoplastic for use in gears, cam mechanisms, guides, bearings/bushings, and parts requiring precise tolerances. The reasons for its popularity are its low friction tendency, high dimensional stability, and mechanical properties. However, it should be noted that POM's friction and wear behaviour is not constant, and operating temperature is a decisive parameter. As the temperature rises, the magnitude of heating at the contact surface increases, causing the material to soften. This phenomenon can result in elevated wear rates in a wide range of applications. Consequently, it has been emphasised that in moving parts where POM is selected, design measures such as creating the necessary clearance in the geometry to dissipate heat and selecting the appropriate mating surface must be taken, considering not only the initial performance but also the temperatures the part may reach during actual operation (Li et al., 2025).

In the context of sustainability, there is an emergent and burgeoning field of research investigating the utilisation of bio-based reinforcements in lieu of conventional (fossil-based) additives to enhance the tribological performance of POM. Specifically, the incorporation of short cellulose fibre reinforcements has been shown to modify the wear behaviour of POM under specific operating conditions, thereby contributing to enhanced stability in friction. A notable example is a study that reported a substantial enhancement in the wear coefficient under particular load-speed conditions with the incorporation of a low percentage of cellulose fibres. This finding underscores the potential of bio-based fillers derived from renewable sources to substitute for petroleum-based additives, thereby enhancing the performance of POM-based components, particularly in contexts where wear is a predominant factor, such as in agricultural machinery systems. This approach is regarded as a more sustainable improvement strategy, with the potential to reduce the environmental impact of the material by diminishing reliance on fossil raw materials, while concurrently enhancing the wear resistance and service life of POM components (Kneissl et al., 2024).

2.5. Polyvinyl chloride (PVC), Polyethylene terephthalate (PET) and Polyvinylidene fluoride (PVDF)

Polyvinyl chloride (PVC) and polyethylene terephthalate (PET)-based polymers are extensively utilised as thermoplastic materials in the domain of agricultural infrastructure. PVC is particularly favoured in fixed and pressurised systems, such as irrigation pipes, fittings, and valve bodies, due to its chemical resistance, cost-effectiveness, and extensive service life. Conversely, PET finds limited application in agricultural packaging, film, and certain special tribological composites. However, these polymers are optimally suited for fixed or semi-static applications and often lack the requisite performance for machine components that demand high precision and continuous movement.

In contrast, engineering thermoplastics, which offer superior dimensional stability, wear resistance and controlled friction behaviour, are preferred for the moving and non-load-bearing mechanical components of agricultural machinery. In this context, materials such as polyamides (PA), polyoxymethylene (POM) and ultra-high molecular weight polyethylene (UHMWPE) are widely used in bushings, gear-like parts, guides and sliding elements. In comparison with PVC and PET, these materials offer enhanced mechanical reliability and can deliver more balanced performance against vibration, uneven loading and abrasive particles encountered in field conditions.

In recent years, research into the behaviour of polymers with more advanced engineering properties, such as polyvinylidene fluoride (PVDF), in gear and wheel applications has attracted attention. PVDF, with its high mechanical strength, good chemical resistance and temperature stability, demonstrates that polymer gears can move beyond being merely light-load-bearing elements to take on more active roles in transmission and control subsystems. Research undertaken in this field has highlighted the necessity for a comparative analysis of the service life, wear mechanisms and failure modes of PVDF-based gears in relation to metal and other polymer alternatives. These findings suggest that polymer gears can be regarded not only as auxiliary components in agricultural machinery, but also as functional power transmission elements, provided that appropriate design and material selection are employed (Muratović et al., 2025).

3. DESIGN-RELEVANT MATERIAL BEHAVIOUR OF THERMOPLASTICS

3.1. Chemical Resistance and Ageing

In the selection of thermoplastics for systems that work with chemicals, such as sprayers and fertiliser spreaders, the material's chemical resistance properties are a key consideration in the decision-making process. However, these properties alone are insufficient. It is also necessary to take into account the material's oxidation under UV light and its mechanical behaviour, specifically the formation of temporary hardening followed by embrittlement. Polymer parts used in agricultural machinery systems are often exposed to UV radiation, temperature fluctuations, and oxygen in open environments. In such conditions, the process of photo-oxidative ageing develops within polymers, resulting in a range of undesirable effects, including colour fading, surface cracks, reduced mechanical properties, and embrittlement over time (Rodriguez et al., 2020). Consequently, the reliability of polymer components operating in outdoor environments is contingent not only on the selection of the base polymer, but also on the judicious formulation employed to regulate the ageing rate. The extant literature indicates that HALS (Hindered Amine Light Stabilisers) type UV stabilisers have been shown to significantly retard photo-oxidative degradation by suppressing the formation of free radicals, while primary and secondary antioxidants contribute to the preservation of mechanical properties by controlling oxidation chain reactions (Jiang & Zhang, 2021). In addition, it has been demonstrated that appropriate pigment strategies can delay the progression of surface damage by limiting the penetration of UV radiation into the polymer. The type and quantity of these additive systems must be evaluated in conjunction with the sun exposure duration of the relevant machine component, operating temperature, chemical contact conditions, and targeted service life (Allen & Edge, 2021).

3.2. Creep, Stress Relaxation, and Dimensional Stability

A significant distinction between thermoplastics and metals pertains to their time-dependent deformation behaviour under load. This phenomenon is characterised by creep and stress relaxation. Creep signifies the sustained increase in deformation over time when a component is exposed to a constant load or stress (Simões et al., 2023). Stress relaxation, conversely, is the decline in stress over time in a material subjected to constant deformation (Noyel et al., 2024). Within the context of agricultural machinery systems, tanks, elongated console covers, brackets, suspension components, and non-load-bearing components frequently function for extended periods under low-to-medium stresses. Consequently, creep behaviour may manifest in practice as sagging, permanent deformation, and alignment issues. Conversely, stress relaxation in bolted or clamped connections, clamps, and sealing surfaces can lead to a decrease in clamping force, loosening, and loss of sealing. Particularly in semi-crystalline thermoplastics such as HDPE, increased molecular mobility with rising temperature significantly increases both creep rate and stress relaxation tendency. Therefore, design based solely on short-term strength or instantaneous stress levels is insufficient; the interaction of load, time and temperature must be considered together in the design. This approach has a direct impact on the determination of the safety factor, the cross-section thickness and roof (main body) design, the use of metal-supported connections, the connection geometry, and the orientation of the parts. Therefore, in HDPE and similar thermoplastics, it is essential to evaluate the data obtained from short-term tests in a way that represents long-term behaviour. If possible, this evaluation should be verified with long-term tests or modelling approaches as a fundamental design requirement for maintaining dimensional stability throughout the service life (Amjadi & Fatemi, 2021).

3.3. Tribological (wear, friction) Properties

In machine systems utilised in the domains of harvesting and product processing technologies, the friction surfaces of the majority of machine components are characterised by the presence of numerous particles, including but not limited to soil, plant residues, and fertiliser crystals. These particles infiltrate the interstices between the two surfaces, thereby modifying the system's friction regime. Typically, the two-body friction condition, wherein two solid surfaces engage in sliding motion, evolves into a three-body wear condition due to the introduction of a third phase, namely the particles, within the system. In this case, the acceleration of wear is not only attributable to material-material interaction, but also to the abrasive effect of the particles on the surfaces, the formation of micro-scratches on the surface, and the subsequent transformation of these scratches into crack initiation points over time. Furthermore, as these particles can also damage the coated film layer on the surface, friction-induced heat increase occurs more easily during sliding, and the rise in temperature can increase the tendency of polymers to soften, causing wear to accelerate further. Therefore, when selecting engineering thermoplastics such as UHMWPE, PA (PA6/PA66) and POM, the choice should not be based solely on a single criterion such as the dry friction coefficient-low, but also the volumetric wear rate of the material in an abrasive environment, the friction-induced temperature increase, and the potential of this increase to alter the material properties (softening, surface film formation, tendency for adhesive wear, etc.) must be evaluated together. In summary, the objective of tribological design in agricultural machinery should be twofold: to minimise friction and to ensure stable friction, low wear, and controllable temperature in dirty/abrasive environmental conditions (Tong et al., 2006; Walczak & Caban, 2021).

4. MANUFACTURING - DRIVEN PERFORMANCE OF THERMOPLASTICS IN AGRICULTURAL MACHINERY

The utilisation of thermoplastic materials in agricultural machinery systems is predominantly attributable to their capacity to be fabricated in intricate geometries in a cost-effective and reproducible manner through diverse production methodologies. The extant literature unequivocally substantiates that the mechanical and tribological efficacy of thermoplastic components in field conditions is contingent not solely on the properties of the base polymer, but also on the fabrication method, the geometric characteristics formed by this method, and the microstructure that is the consequence of the process (Mejia et al., 2021). In this context, the production method-geometry-performance relationship provides a fundamental engineering framework explaining why thermoplastics are preferred in agricultural machinery.

- **Injection Moulding:** Injection moulding is a widely utilised manufacturing process for the production of functional and precision components for agricultural machinery systems, owing to its high dimensional accuracy and consistent quality. Typical applications of this method include gears, bushing bodies and guide elements, manufactured from polyoxymethylene (POM) and polyamide (PA), in addition to housings fabricated from polypropylene (PP). However, the presence of weld lines in areas where molten flows converge during injection moulding can result in the formation of weak points, which can compromise the impact resistance and fatigue life of polymer components. Furthermore, the presence of sharp corners and abrupt cross-sectional changes can lead to stress concentrations due to the notch effect (Bao et al., 2025). In glass fibre-reinforced systems, the alignment of fibres in the flow direction instigates mechanical anisotropy, thereby rendering part performance contingent on the loading direction. These findings indicate that mould design and flow directions in agricultural machinery parts produced by injection moulding should be addressed with a performance-oriented approach. (Zhong et al., 2020; Żurawik et al., 2022).

•**Extrusion:** The extrusion method has been extensively utilised in the fabrication of pipes, hoses and profiles within agricultural systems, due to its capacity to facilitate the production of products characterised by a constant cross-section and uninterrupted length. The efficacy of thermoplastic components manufactured through extrusion is contingent upon factors such as cross-sectional homogeneity, optimal cooling-drawing balance and process stability. It has been documented those discrepancies in thickness distribution, particularly in pipe applications, result in ovalisation under internal pressure and protracted dimensional stability concerns. Nevertheless, through the implementation of multi-layer extrusion techniques, it is possible to develop functional designs that offer enhanced chemical resistance in the inner layer and UV and environmental resilience in the outer layer. This attribute confers a substantial design benefit for components subjected to outdoor conditions within agricultural machinery (Agassant & Demay, 2022; Deveci et al., 2021; Fuentes et al., 2025; Hyvärinen et al., 2020; Nastaj & Wilczyński, 2021; Wei et al., 2022)

•**Rotational Moulding:** Rotational moulding is a method of manufacturing large-volume, hollow thermoplastic components in a single piece, which is employed extensively in the field of agricultural machinery, particularly in the fabrication of HDPE-based liquid tanks (Hejna et al., 2020). The mechanical and thermomechanical behaviour of rotomoulded components is contingent on process parameters such as wall thickness homogeneity, powder sintering/coalescence degree, and cycle time-thermal history (Tyukanko et al., 2023). Consequently, it can be posited that process monitoring and quality control approaches assume a pivotal role in tank production. The extant literature reports that microstructural defects (e.g. porosity/voids) in rotomoulded PE systems, which are dependent on process/production conditions, have the capacity to negatively affect performance criteria such as impact resistance. Furthermore, it is reported that these performance differences can be revealed by final product testing (Torres & Aragon, 2006). In polymers suitable for rotational moulding, it has been determined that time-dependent deformation under long-term loading exhibits significant differences depending on the material type (Pozhil et al., 2022). Therefore, in the design of such polymers, not only short-term mechanical properties but also long-term mechanical behaviour must be considered (Pozhil et al., 2022). These findings reveal that process optimisation and thickness/quality control in agricultural machine tanks produced by rotational moulding are critically important for long-term service performance (Tyukanko et al., 2023).

A review of the extant literature reveals a direct correlation between the performance of thermoplastics in agricultural machinery systems and their geometry and microstructure, which are shaped by the production method (Cravero et al., 2025). In the context of injection moulding, it has been reported that the flow field in reinforced systems determines fibre orientation, thereby creating mechanical anisotropy and rendering performance sensitive to the loading direction (Kim et al., 2001). Whilst extrusion is highly effective in the production of continuous and constant cross-section components, it is the process parameters and cooling/flow conditions that are decisive for product quality and performance (Hyvärinen et al., 2020). Conversely, rotational moulding is a method that enables the production of hollow parts in a wide range of dimensions and thicknesses. Furthermore, process/mixture strategies have been shown to significantly affect morphology and mechanical outputs (Ruiz-Silva et al., 2021).

5. DESIGN AND SERVICE - BASED SELECTION OF THERMOPLASTICS IN AGRICULTURAL MACHINERY

The selection of thermoplastics for components forming the agricultural machinery system is based on the exposure environment (chemical/UV/humidity), load type (static-dynamic), tribological regime (dry/boundary lubrication/particulate friction), and the interaction between geometry and microstructure shaped by production.

•**High chemical exposure and corrosion risk:** In areas exposed to chemicals such as fertilisers and pesticides (e.g. storage, filling/emptying lines, covers, connecting elements), the primary risks are not only metal corrosion but also chemical swelling, stress cracking and oxidative ageing on the polymer side. Polyolefins such as PE and PP are commonly preferred in such environments due to their general chemical stability and wide range of applications. PE has been reported to exhibit a relatively stable behavioural response in common acid and alkali environments; however, prolonged chemical exposure may still induce degradation phenomena depending on environmental conditions and service duration (Yao et al., 2022). However, chemical resistance varies not only depending on the polymer type but also on temperature, contact time, contact under stress, and the additive system.

•**Risk of friction and wear:** In the context of agricultural machinery systems, tribology frequently occurs under conditions that are not dry and clean. Soil, plant and fertiliser crystals have the capacity to transform friction from a two-body contact into a three-body abrasive regime. In three-body wear models, variables such as particle size/hardness and contact pressure have been demonstrated to significantly affect polymer wear rates (Cenna et al., 2003). Consequently, the selection approach for friction-wear critical parts (slides, guides, bushings, gears, chain guides, material flow areas) can be elucidated as follows:

UHMWPE (Ultra-High Molecular Weight Polyethylene): The material exhibits low friction and wear resistance, and it has been reported that its friction and wear behaviour can be improved with different formulations (Wang et al., 2025).

PA (Polyamide; PA6/PA66): The substance has been utilised in the fabrication of bushings, bearings, and gears. However, it has been documented that moisture levels can significantly modify the tribological behaviour of the component. Specifically, moisture has been observed to reduce the friction coefficient and wear values, particularly in the case of PA66 (Wu et al., 2024).

POM (Polyoxymethylene/Acetal): A thermoplastic that is characterised by its high dimensional stability and tribological properties. However, experimental findings have indicated that the friction and wear coefficients of polyoxymethylene (POM) may increase with rising operating temperatures (Li et al., 2025).

•**Long-term load-bearing conditions:** A prevalent risk identified in components such as tanks, suspension elements, brackets, long console covers, and carrier housings pertains to creep, defined as the time-dependent deformation of thermoplastics, which is accompanied by the concomitant loss of alignment and sealing. The experimental studies conducted on HDPE demonstrate that temperature and stress level exert a significant influence on long-term deformation curves. Furthermore, these studies illustrate that modelling approaches can be utilised to predict long-term behaviour from short-term tests (Mao et al., 2021). The general approach advocated is to optimise the thickness of the top cover and upper panel geometry in HDPE and PP components, in order to mitigate creep-induced deformation under sustained service loads. It is also stated that reinforced systems should be preferred when necessary (Amjadi & Fatemi, 2021).

•**The effect of UV in outdoor environments:** Outdoor exposure in agricultural machinery often limits the service life of thermoplastics through the UV+oxygen+temperature cycle. It has been established that a significant proportion of polymers, including PP, exhibit sensitivity to oxidative degradation when exposed to UV. Consequently, the utilisation of UV stabilisers as performance-protective agents in industrial formulations has become a prevalent practice. It has been determined that light stabilisers, such as HALS and UV absorbers, contribute to the longer-term preservation of the component's mechanical properties. For instance, combinations of HALS and nano ZnO on PP have been shown to increase the component's UV resistance. In PE/PP materials containing HALS additives, UV-induced degradation occurs more slowly, and the material can preserve its properties for longer than unstabilised polymers.

6.SUSTAINABILITY ASSESSMENT OF THERMOPLASTICS IN AGRICULTURAL MACHINERY SYSTEMS

The assessment of thermoplastics in agricultural machinery systems in terms of sustainability is not confined to the question of whether they are recyclable. The key determining factor is how the material's environmental impact is managed throughout its life cycle (production, use, maintenance, and end-of-life). Current literature clearly indicates that product design, separability, and recycling infrastructure must be addressed together to strengthen circularity in polymers (Geyer et al., 2017; Hopewell et al., 2009; Ragaert et al., 2017).

The agricultural sector is one of the areas in which there is intensive use of plastic, and the formation of microplastics and their subsequent dispersion in the environment are particularly salient issues. It has been reported that microplastics can enter the soil environment in agricultural systems through plastic-based agricultural inputs, residues, and external transport, and have been reported at measurable levels in agricultural soils (Bläsing & Amelung, 2018; de Souza Machado et al., 2018). Therefore, the design objective should be to develop solutions that perform the same function with a longer lifespan and lower environmental impact. In this context, the following four fundamental design principles can be highlighted for sustainable material selection:

•**Long-lasting design:** The provision of designs that provide appropriate stabilisation against UV and oxidative ageing, protective solutions in wear-critical areas, and ease of maintenance has been demonstrated to prevent the early replacement of parts. The extant literature emphasises that extending product life directly reduces the overall environmental impact (Hopewell et al., 2009).

•**Design for easy assembly and recovery:** The ease with which components can be disassembled, the avoidance of permanent and non-separable joints, and the reduction of details that complicate recycling all serve to increase recovery efficiency. It is an established fact that design decisions have a direct impact on recycling value (Ragaert et al., 2017).

•**Single-polymer approach:** The utilisation of single-polymer designs for machine components has been demonstrated to facilitate separation and classification processes. Conversely, multi-material or multi-layer structures have been shown to impede the recycling process. As Ragaert et al. (2017) have demonstrated, this situation is of particular significance in studies evaluating multi-layer polymer structures from a circular economy perspective.

•**Use of recycled and bio-based content:** Whilst the utilisation of recycled materials indubitably offers certain environmental advantages, it is imperative that variability in mechanical and thermomechanical properties is given due consideration from a design perspective. Recent studies have examined the performance differences of recycled PP/HDPE blends and their long-term behaviour during use (Vilaplana & Karlsson, 2008). However, before such materials can be favoured in design, it is essential that their compatibility with the part's loading conditions, environmental exposure, and safety factors is verified through experimental validation and engineering assessments.

7. ENGINEERING - GUIDED SELECTION OF THERMOPLASTICS FOR AGRICULTURAL MACHINERY COMPONENTS

The selection of thermoplastics for utilisation in agricultural machinery systems is contingent not solely on the material's fundamental mechanical properties, but also on numerous engineering parameters. Such parameters include the subsystem within which the component is to be employed, the environmental conditions to which it is exposed, the type of loading to which it is subjected, and the anticipated service life. In this context, the systematic and comparative presentation of suitable thermoplastics for different agricultural machinery components is of paramount importance. Such a presentation is both instrumental in accelerating the design process and in preventing field-related failures. Table 2 provides a concise overview of the most notable thermoplastic polymers selected for these components, the underlying reasons for their selection, and their critical design and performance characteristics, based on the fundamental component groups commonly employed in agricultural machinery.

Table 2. Selection of thermoplastics according to components used in agricultural machinery systems

Machine components	Recommended thermoplastic	Justification	Main risks/limitations
Sprayer tank	HDPE (rotational moulding)	High chemical resistance, corrosion resistance, single-piece production, low density	Creep under long-term load, UV ageing, (stabiliser required)

Sprayer fan housing (air duct)	PP, GF/PP	Low weight, vibration damping, moulding flexibility	Impact sensitivity, weak areas in glass fibre systems due to fibre orientation
Seed hopper for seeding machine	HDPE, PP	Corrosion-resistant structure, smooth surface, homogeneous flow, low maintenance	Risk of permanent deformation (load + temperature), roof design required
Seed drill fertiliser hopper	HDPE, PP (stabilised)	Chemical resistance, long service life compared to metal alternatives	Chemical + UV combination (requires antioxidant/UV additive)
Harvesting machine body panels	PP, GF/PP	Weight reduction, noise and vibration damping	Risk of localised breakage due to impacts from stones, debris, etc.
Harvesting machine air ducts	PP, PE	Low friction, production of complex duct geometry	Loss of rigidity with temperature increase
Sliding rail / wear plate	UHMWPE	Very low friction coefficient, high wear resistance	Sensitivity to load-speed-temperature limits
Sliding bearing / bushing	PA6, PA66	Good tribological properties, quiet operation compared to metal bearings	Moisture absorption (dimensional change), pressure-speed limits
Gear / precision moving part	POM	Dimensional stability, low friction, good mechanical balance	Increased wear with rising temperature
Pressurised irrigation pipe	HDPE, PVC	Corrosion resistance, low roughness, long service life	Creep (HDPE), temperature-dependent pressure drop
Connection elements / protective boxes	PP	Low cost, chemical resistance, easy injection	Risk of brittleness under UV exposure
Hoses and flexible lines	PE, elastomer-modified PP	Flexibility, chemical resistance	Ageing and cracking (UV/ozone)

A comparative assessment of the available materials has been presented in tabular form. This analysis indicates that a single ideal material cannot be selected for use in the manufacture of agricultural machinery components. Polyolefins (e.g. PE and PP) are preferred in applications where chemical exposure and environmental effects are dominant, such as in the storage and preservation of foodstuffs. In contrast, engineering thermoplastics (e.g. UHMWPE, PA and POM) are preferred in moving parts that require friction, wear and precise tolerances. In components that carry long-term loads or where dimensional stability is critical, creep behaviour has become an integral part of the design, and a shift to geometry optimisation or reinforced systems is inevitable. When evaluated from this holistic perspective, the common consensus revealed by the table is that the selection of thermoplastic materials must be considered within the framework of the interaction between the part, environment, load and production method, and that a successful design is based on the harmonious matching of material properties and field conditions.

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CHAPTER 6

THE RISING VALUE AND ADVANTAGES OF BLUEBERRY (*Vaccinium* spp.) IN THE EASTERN BLACK SEA REGION UNSURLAR

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INTRODUCTION

In recent years, interest in high value-added fruit species within the framework of agricultural production and rural development has increased markedly. This trend is closely related not only to the nutritional quality of the product but also to environmental sustainability and economic resilience. In this context, blueberry (*Vaccinium* spp.) has risen to a preferred agricultural product due to its bioactive compound profile and increasing global demand. In the process of transforming production patterns in Türkiye, increasing income per unit area in regions with pronounced ecological constraints has become a fundamental objective. Within this framework, the Eastern Black Sea Region, which stands out with its humid climatic conditions and acidic soil characteristics, offers remarkable potential for the development of additional production models beyond conventional cropping patterns. However, the effective utilization of this potential is possible only through a holistic consideration of all systems rather than solely the presence of suitable ecological conditions. Within the modern agricultural paradigm, the utilization of by-products has increasingly become an important element in enhancing resource efficiency. This approach necessitates the evaluation of blueberry production systems not only in terms of the primary product but also in terms of their capacity to generate multidimensional added value. This review aims to examine, through a literature-based approach, the current production structure of blueberry (*Vaccinium* spp.) cultivation in the Eastern Black Sea Region, its value-added generation capacity, and its potential for integration into regional agricultural systems.

Blueberry is a berry fruit belonging to the genus *Vaccinium* within the family Ericaceae, which is predominantly distributed in temperate climate zones worldwide and prefers acidic soil conditions (Arslaner and Salık, 2020). In terms of natural distribution areas, Türkiye, particularly the Eastern Black Sea Region, is an important genetic resource area where species such as *Vaccinium arctostaphylos* and *Vaccinium myrtillus* grow naturally (Okan et al., 2014).

Across the region, blueberry is integrated into local production and consumption culture and is known by different names such as “likapa,” “ayı üzümü,” “çay üzümü,” and “lifor.” In addition to fresh consumption, it is widely utilized by local communities in the production of traditional products such as fruit juice, jam, and marmalade (Gürdal, 2021).

In recent years, blueberry cultivation has expanded rapidly within planned agricultural production systems beyond its natural distribution areas. This development has revealed a considerable economic value throughout Türkiye, particularly in the Eastern Black Sea Region. Indeed, according to data from 2015, production carried out on a total area of 533 decares in the provinces of Rize and Trabzon resulted in approximately 180 tons of product and generated an income of around 5 million TL (Akbulut and Bakoğlu, 2017). Over the past two decades, global production of blueberry (*Vaccinium spp.*) has increased rapidly. According to data from the International Blueberry Organization, as of 2023, global production reached 1.78 million tons, while the cultivation area exceeded 262,000 hectares (IBO, 2024). These values indicate an approximately twofold increase compared to 2013. Although the American continent holds a significant share in global production, China became the world’s largest producer in 2023 with a production volume of 560,000 tons (Zhou et al., 2025).

Blueberry (*Vaccinium spp.*) is globally defined as a “superfruit” due to its high antioxidant capacity and rich functional component content (Krishna et al., 2023). Its structure, which is rich in anthocyanins and phenolic compounds, has been associated with various health benefits; this has led to increased demand both for fresh consumption and in the processed food sector (Wang et al., 2025). The growing global demand has markedly enhanced the economic potential of blueberry production, particularly in the Eastern Black Sea Region, in areas possessing microecosystems favorable in terms of climate and soil conditions (Gürdal, 2021).

In Türkiye, blueberry cultivation has expanded through open-field and protected production systems in the Black Sea Region primarily, as well as in the Marmara, Aegean, and Mediterranean regions (Atacan and Yanık, 2017; Çelik and Acar, 2025). The rural population living in the mountainous and rugged areas of the Black Sea Region, despite limited agricultural land, contributes to household economies by collecting these species from natural populations or cultivating them in small-scale production areas, thereby supporting rural production systems based on the sustainable use of natural resources (Türkmen et al., 2019). The aim of this review is to evaluate the current status of blueberry (*Vaccinium* spp.) cultivation in the Eastern Black Sea Region, its regional potential, and the ecological and economic advantages it offers in light of the current literature.

CURRENT AGRICULTURAL POTENTIAL OF THE EASTERN BLACK SEA REGION IN TERMS OF BERRY FRUITS

Across Türkiye, agricultural potential is defined as the ability to generate economic benefits through the combination of multiple factors, including the presence of favorable climatic and edaphic conditions in a given geography, the availability of extensive production areas, and the existence of a developed agricultural industry for product processing and utilization (Öztürk and Serttaş, 2018). Within this framework, the Black Sea Region holds an important position in national agricultural production, ranking fourth in terms of total agricultural land area and second—immediately after the Aegean Region—with respect to fruit cultivation areas (Öztürk and Serttaş, 2018). The region's distinctive ecological constraints, rugged geographical structure, and the continuous fragmentation and reduction of landholdings through inheritance have triggered a need to shift toward crops capable of providing higher returns per unit area (Akbulut et al., 2017). As a result, interest in berry fruits such as kiwi (*Actinidia deliciosa*), strawberry (*Fragaria* × *ananassa*), rosehip (*Rosa canina* L.), and blackberry (*Rubus spp.*) has increased markedly, and new orchards have begun to be established; however, factors such as insufficient technical knowledge, high establishment costs, and marketing difficulties limit the wider expansion of these crops (Akbulut et al., 2017).

When regional concentration of fruit production is considered, Rize (40.8%) and Trabzon (16.5%) have been identified as the leading fruit production centers among the Eastern Black Sea provinces (Öztürk and Serttaş, 2018). Textural analyses of agricultural soils in the Central and Eastern Black Sea regions indicate that a large proportion of the lands (75.30%) have a loamy structure and that organic matter levels are generally within medium to high ranges (Özyazıcı et al., 2016). However, the wide range observed in soil pH values (4.5–8.5) and phosphorus deficiency detected in 58.83% of the lands necessitate the diversification of soil improvement and nutrient management practices on a regional basis (Özyazıcı et al., 2016). Blueberry, which attracts attention due to its high antioxidant content and added value, is regarded as the strongest future berry fruit potential, as it largely meets the requirements of the region's cool and humid climate and acidic soil structure (Akbulut et al., 2017). Therefore, in order to maximize existing ecological and industrial advantages, the dissemination of high-density dwarf fruit production systems focusing on the selection of regionally suitable species/cultivars and rootstocks is recommended as an important strategic practice (Öztürk and Serttaş, 2018).

GENERAL ADVANTAGES PROVIDED BY BLUEBERRY (*Vaccinium corymbosum* L.) TO THE REGION

The agricultural structure of the Eastern Black Sea Region is largely based on tea and hazelnut production. The region accounts for the entirety of Türkiye's tea production and approximately two-thirds of its hazelnut production (Öztürk and Serttaş, 2018). However, the increasing fragmentation of land through inheritance and the restrictive effects of topography on agricultural activities have directed producers toward alternative crops that provide higher income per unit area (Akbulut et al., 2017; Keleş, 2024).

This tendency corresponds to the strategy commonly observed in developing economies of transitioning from low value-added production models to high value-added agricultural products (Soyyiğit and Yavuzaslan, 2019). In this transformation process, the Value-Added Agriculture (VAA) approach plays a fundamental role. VAA represents a production concept aimed at increasing the economic value of traditional agricultural products through processing, transformation, or alternative marketing methods (Özkan, 2024). The adoption of this approach not only increases farmers' incomes but also contributes to the promotion of environmental sustainability and social equity (Özkan, 2024). In this context, blueberry (*Vaccinium spp.*) is considered one of the prominent fruit species within the scope of the Value-Added Agriculture approach due to its suitability for processing in addition to fresh consumption, marketing diversity, and high unit sales value. Furthermore, the potential applications of not only its fruits but also its leaves, roots, and flowers in sectors such as pharmaceuticals and cosmetics diversify the added value it offers to the regional economy (Yıldız et al., 2025). In this respect, blueberry stands out for the Eastern Black Sea Region not only as an agricultural product with high added value but also as an important functional food source that supports public health (Zahra et al., 2023). The most fundamental advantage provided by blueberry for regional development and public health is its high bioactive compound content (Zahra et al., 2023). Polyphenolic compounds, known for their abundant anthocyanin pigment content, confer strong antioxidative and anti-inflammatory activities to the fruit (Zahra et al., 2023). Scientific studies indicate that blueberry possesses functional properties that reduce the risk of heart disease, diabetes, and neurodegeneration, in addition to exhibiting specific nutritional properties such as neuroprotective, osteoprotective, renoprotective, and ophthalmoprotective effects (Zahra et al., 2023).

The favorable climate and soil conditions of the Black Sea Region significantly enhance the fruit-growing potential of the region (Öztürk and Serttaş, 2018). In recent years, interest in berry fruits such as blueberry, kiwi, and blackberry has increased rapidly; in parallel, new orchards have begun to be established in the region (Akbulut et al., 2017). It is reported that Türkiye has also adapted to this global trend, with a marked increase recorded in blueberry cultivation areas and production volume (TÜİK, 2024). In addition, the implementation of modern cultivation systems such as dwarf fruit production increases the economic returns obtained from regional fruit growing (Öztürk and Serttaş, 2018).

Nevertheless, several limiting factors exist in newly established blueberry orchards, including high establishment costs, lack of technical knowledge, and marketing problems (Akbulut et al., 2017). Furthermore, the inadequacy of traditional practices aimed at protecting crops from wild animals in cultivated areas has emerged as an important issue requiring solutions in terms of product security (Keleş, 2024).

These advantages offered by blueberry for the region stem from the plant's high adaptability to the temperate climate zone and its strong compatibility with the unique ecological conditions of the Eastern Black Sea Region in particular (Arslaner & Salık, 2020). Expected increases in precipitation and milder winter conditions in the Black Sea Region provide a favorable production environment for blueberry cultivation (Oğuz et al., 2023). This adaptation process is further reinforced by the suitability of the regional soil structure and climatic characteristics, which allow blueberry cultivars to develop efficiently (Türkmen et al., 2019). Moreover, while climate change scenarios lead to significant changes in cropping patterns across different regions of Türkiye, species such as blueberry that are capable of adapting to environmental conditions offer a strategic advantage against these changes (Oğuz et al., 2023).

The climatic structure of the Eastern Black Sea Region provides a suitable basis for the adaptation of Northern Highbush Blueberry (Northern Highbush Blueberry – NHB) types, which naturally experience cold winters and have high chilling requirements (chilling hours) (Ru et al., 2024). While minimum winter temperatures stand out as one of the critical abiotic factors determining yield levels in the plant (Zydlik et al., 2019), abiotic stress conditions such as low temperatures may positively affect fruit quality by triggering the accumulation of antioxidants in the fruit (Krishna et al., 2023). Blueberry (*Vaccinium corymbosum* L.) has specific soil requirements, and the naturally acidic soil structure of the region provides an advantageous natural environment for cultivation (Zydlik et al., 2019). The use of beneficial bacteria combinations in organic farming systems offers the potential to improve plant yield, fruit quality, and soil health, thereby playing an important role in achieving sustainable and innovative agricultural goals in the region (Yu et al., 2020).

In addition to its climatic advantages, blueberry has significant potential to support rural development through its contributions to the regional economy (Gürdal, 2021). Considering the challenging terrain structure and rich plant biodiversity of the Eastern Black Sea Region, the idea of evaluating the region as a "health and functional food center" based on plant production rather than industry is further strengthened through blueberry cultivation (Okan et al., 2014).

ECONOMIC CONTRIBUTIONS OF BLUEBERRY (*Vaccinium* corymbosum L.) TO THE REGION

Blueberry (*Vaccinium* spp.) is recognized globally as one of the most popular and nutritious fruits (Zahra et al., 2023). Due to its richness in antioxidant compounds such as dietary fiber, vitamins, minerals, phenolic acids, and flavonoids, it is considered a food source with high nutrient density (Zahra et al., 2023). The health-promoting (pro-health) properties of this fruit have significantly increased interest in its cultivation worldwide and have led to a remarkable rise in global fruit production (Zydlik et al., 2019). Recognized as one of the fruit species with the highest commercial and production expectations worldwide, blueberry offers significant export and income growth potential for producers in the Eastern Black Sea Region, driven by a high average annual increase of 6.1% in global demand (Lobos and Hancock, 2015).

For the sustainable development of cultivation in the region, it is emphasized as a necessity to implement solution proposals addressing the problems faced by producers during cultivation and post-harvest transportation stages (Yıldız et al., 2025). Particularly, considering the adaptation of Northern Highbush blueberry types, the acidic soil structure of the region, and its potential to meet winter chilling requirements, it is important to investigate the synergistic effects of genotype and environmental conditions on fruit quality and antioxidant content (Arslaner and Salık, 2020; Çelik and Acar, 2025; Pepe et al., 2023). In addition, the optimization of cultivation techniques, especially the evaluation of the effects of modern production systems such as soilless agriculture and pot cultivation on fruit yield and quality, is required (Çelik and Acar, 2025; Pepe et al., 2023).

From an economic perspective, blueberry cultivation increases income per unit area in small and fragmented land structures and provides income diversification through its suitability for conversion into fresh and processed products. In addition, the increased labor demand during harvesting, packaging, and cold chain processes supports regional employment, while its export potential offers a significant advantage for the regional economy in terms of foreign currency inflow.

CONCLUSION

The Eastern Black Sea Region is one of the most favorable production areas in Türkiye for blueberry (*Vaccinium spp.*) cultivation, owing to its humid climatic conditions, acidic soil structure, and ecological characteristics that meet natural chilling requirements. Considering the region's fragmented land structure and limited agricultural areas, blueberry occupies a position consistent with the value-added agriculture approach due to its high return per unit area, processability capacity, and increasing global demand. Current evidence indicates that blueberry offers significant potential not only in terms of agricultural production but also with respect to supporting rural employment, increasing income diversification, and providing export-oriented economic contributions.

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CHAPTER 7

SUSTAINABILITY AND FOOD SECURITY: ENTANGLED CHALLENGES OF CLIMATE CHANGE

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1. INTRODUCTION

Climate change is is considered the greatest challenge facing our planet, due to its interlinked and cascading impacts. It affects the essential interactions among air, water, and soil, fundamentally threatening the sustainability of natural ecosystems and human societies.

The world's population is expected to reach around 10 billion by 2050. Agriculture faces a crucial responsibility under climate change: sustainably feeding exploding global population and ensuring of agro-based industries. According to the World Resources Institute (WRI, 2025), currently, nearly 800 million people worldwide experience hunger. Institute also indicates that to meet food demands by 2050, we must compensate a 56% difference between current supply and future needs.

The impacts of climate change on food security poses a major global concern, with multifaceted implications on ecological systems, human health, economic stability, and geopolitical dynamics. Shifts in temperature and rainfall patterns along with rising sea levels, and the increased frequency of extreme weather events are reducing crop and livestock productivity. These changes lead to food and water scarcity, price volatility and market shocks that consequently hindering every dimension of the agricultural supply chain. Anticipated worsening impacts putting global food security and the livelihoods of hundreds of millions of people at risk and driving migration flows, principally toward urban areas (Adger et al., 2020).

At the same time, unsustainable agricultural systems are among the principal drivers of global ecosystem degradation and galvanizing climate change. Agriculture has dominates around 40% of Earth’s ice-free ecosystems (Yang et al., 2024) by encompassing nearly 50% of the world's vegetated land and accounting for 70% of freshwater withdrawals (FAO, 2025a), a significant contributor to deforestation especially in tropical regions (WRI, 2025) and agrifood systems account for about one-third of total greenhouse gas emissions (Crippa et al., 2021).

The agricultural sectors, which include crop and livestock production, forestry, fisheries and aquaculture, are a major contributor to global greenhouse gas emissions and other environmental pressures, including air, water and soil pollution, habitat degradation, deforestation, biodiversity loss and the emergence of zoonotic and food-borne diseases. (WHO, 2025) In turn, climate change is jeopardizing food security and the resilience of agrifood supply chains, with climate-induced natural hazards leading to production losses that exacerbate vulnerability in agroeconomies and undermine rural development.

As demand for agricultural commodities is projected to increase substantially (by 35–56% between 2010 and 2050), (van Dijk et al., 2021) pressure is intensifying to further intensify production systems or expand cropland through land-use change. While such responses may increase short-term food output, they are also likely to accelerate conversion of natural ecosystems, resulting in biodiversity loss and degradation of critical ecosystem services, including soil fertility, water regulation, and climate regulation. These land-use dynamics increase exposure and vulnerability of poor and marginalized populations, thereby amplifying long-term social, ecological, and food-system risks.

Food consumption patterns and production methods have profound implications for both human and ecosystems health. Each lifecycle phases of agrifood systems —including production, processing, transport, distribution, preparation, consumption, and waste management—generates greenhouse gas emissions that contribute to climate change. These emissions originate from on-farm crop and livestock production, land-use change associated with deforestation, biomass burning, and peatland degradation, as well as post-production activities across the agrifood supply chain, including processing, trade, distribution, consumption and waste disposal (Dussi, M. C., 2025). A growing number of studies indicate that the impact of the global agrifood system on climate change increases substantially when pre- and post-production processes across supply chain logistics, food processing and retail, consumption patterns, and waste management are taken into account. When all agrifood system activities are collectively considered, total emissions are estimated to represent approximately 20–40% of global anthropogenic greenhouse gas emissions (UNIDO, 2025; Mandouri et al., 2025; Crippa et al, 2021).

The agricultural sector faces two interlinked challenges: sustainably increasing productivity to meet rising global food demand, and addressing climate change by reducing greenhouse gas emissions and enhancing adaptive capacity and resilience of production systems. Since the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015 under the 2030 Agenda, there has been growing recognition that transforming agrifood systems is essential for reducing environmental pressures while enhancing food security under climate change. As a result, agricultural sustainability has become a central focus of international policy agendas, including the UN Food Systems Summits, the UN Framework Convention on Climate Change Conferences of the Parties (COPs), and the IPCC Sixth Assessment Report (AR6). Enhancing sustainable agriculture within the broader food system framework requires strategic policies to simultaneously advance climate mitigation and adaptation, safeguard biodiversity and natural resources, and improve public health, while strengthening the resilience and long-term sustainability of agrifood systems.

1.1 Ensuring sustainability in agrifood systems

Sustainable development is based on three fundamental pillars: social, economic and environmental. Sustainability in agriculture defined as “food system practices that contribute to long-term regeneration of natural, social, and economic systems, ensuring the food needs of the present generations are met without compromising food needs of future generations” (HLPE, 2020).

Sustainable agriculture constitutes a fundamental component of food security and sustainable development, directly contributing to the achievement of multiple SDGs related to climate change mitigation and food security. Specifically, it supports poverty reduction through the creation of resilient and diversified livelihoods (SDG 1: No Poverty); advances food security and improved nutrition through the promotion of sustainable agricultural practices (SDG 2: Zero Hunger); reduces health risks by minimizing the use of harmful chemicals (SDG 3: Good Health and Well-Being); enhances the efficient and responsible use of natural resources (SDG 12: Responsible Consumption and Production); and strengthens the resilience of agricultural ecosystems and rural communities in the context of climate change (SDG 13: Climate Action).

Sustainable agricultural development has a crucial role in achieving food security, improving livelihoods, and safeguarding natural resources. Sustainable agricultural development seeks to enhance productivity while maintaining soil health, improving the efficiency of water and energy use, conserving agricultural biodiversity, reinforcing rural resilience and promoting equity and social well-being (FAO, 2016b). Achieving these objectives requires a holistic consideration of agrifood system. Such an approach integrates coherent strategies across agricultural sectors and throughout all stages of the agrifood value chain, while managing trade-offs among the economic, social, and environmental dimensions of sustainability. Integrated approaches of sustainable agriculture can reduce natural resource depletion, improve the efficiency of natural and financial resource use, and strengthen agricultural food supply chains. Sustainable agricultural development offers a cost-effective pathway to enhance equity, particularly in developing countries, by delivering targeted benefits to small-scale farmers and increasing the resilience of communities most vulnerable to climate-induced risks (UNICEF, 2025).

Transitioning to sustainable agricultural production systems and food value chains requires coordinated action by all stakeholders, including local communities and governments, civil society, and the private sector and green entrepreneurship across the design and implementation of policies, programmes, and investments.

Current strategies for sustainability in agriculture remain insufficient to enable a transition to sustainable agrifood systems. This situation poses a major threat to agricultural communities, especially in developing countries, which are already suffering from poverty, hunger, and malnutrition. Measures such as reducing meat consumption and shifting to plant-based diets like legumes, fruits, and vegetables, decreasing food waste and improving food production through innovative technologies are common components of agrifood system change. However, solely, these measures do not address the deeper institutional, policy, and economic factors that drive unsustainable agrifood systems (McGreevy et. al, 2022). This determination highlights the importance of the IPCC's AR6 discussion of degrowth as a transformative approach for advancing sustainable agrifood systems, emphasizing the need to integrate both socio-economic and ecological sustainability.

Sustainable agricultural practices can contribute to mitigating climate change by enhancing soil carbon sequestration such as reduced tillage, improved grazing management, the restoration of organic soils and restoration of degraded lands. These sustainable management practices include diversified farming systems such as crop rotation, agroforestry, inter cropping, embedding natural habitats, and mixed crop and livestock farming. In extensively managed systems, often characterized by low input agrochemicals, and high diversity croplands with low yields, crop production could be strengthened through conserving agricultural biodiversity by rotating mixed crops and plantings densities, vegetation strips or through agroforestry systems. Intensively managed systems on the other hand, often signified by large tracts of monocultures managed with high agrochemicals, could be diversified through mixed plantings, agroforestry systems including diversified home gardens, boundary planting that involves use of hedgerows or tree breaks, embedding natural habitats e.g., vegetation strips, and diversifying landscapes surrounding croplands.

An increasing body of evidence suggests that sustainable agricultural practices are associated with over 10 % increase in food production (Beillouin et al., 2021; Zhao, 2022), improved economic outcomes over 20% (Himmelstein et al., 2016; Sánchez et al., 2022), around 19% reduced groundwater depletion (Yang et al., 2021; Wang, S. et al., 2023), enhanced carbon mitigation about 11% (Tamburini et al., 2020) and significant gains-over 20%- in biodiversity conservation (Bowman et al., 2013; Mauser et al., 2015; Rosa-Schleich et al., 2019; Jones et al., 2021; Beillouin et al., 2021; Zhao, 2022).

Another promising strategies for agricultural sustainability is ‘climate-smart agriculture’. UN Food and Agriculture Organization (FAO) introduced the concept of climate-smart agriculture in 2010. FAO promotes climate-smart agriculture to transform agricultural production systems and food value chains to support sustainable development and ensure food security under climate change. Climate-smart agriculture provides a framework for stakeholders at all levels to identify agricultural strategies adapted to local conditions, supporting more productive and sustainable agrifood systems including crops and livestocks, forestry, fisheries, and aquaculture (FAO, 2025b).

Objectives of climate-smart agriculture involves improving productivity and livelihoods in a sustainable manner, building resilience and adaptive capacity to climate change, and reducing or removing greenhouse gas emissions where possible. More than 30 countries—predominantly in sub-Saharan Africa—explicitly reference climate-smart agriculture in their Intended Nationally Determined Contributions (INDCs) submitted to the UNFCCC, while many others highlight the strategic role of agriculture in climate action. In line with Türkiye's INDCs, the Ministry of Agriculture and Forestry launched the World Bank–financed Türkiye Smart Climate and Competitive Agricultural Growth Project (TUCSAP) in 2023. With a budget of over TRY 9.17 billion, TUCSAP seeks to enhance the productivity, competitiveness, and climate resilience of the agricultural sector by supporting around 43,000 farmers in adopting smart agriculture technologies (GrowTech, 2023).

1.2 Ensuring food security in agrifood systems

According to the latest State of Food Security and Nutrition in the World (SOFI, 2025) report by the UN World Food Programme, an estimated 8.2% of the global population—approximately 673 million people across Africa, Asia, and Latin America—experienced hunger in 2024. Of these, around 343 million people faced acute food insecurity. Moreover, approximately 2.3 billion people experienced moderate or severe food insecurity, while 2.6 billion were unable to afford a healthy diet. Projections under climate change indicate that hunger will persist, with an estimated 512 million people still affected by 2030. Food insecurity remains disproportionately higher in rural areas than in urban settings and continues to affect women and children most severely. Conflict, climate variability and weather extremes, and economic shocks are key drivers of hunger, food insecurity, and malnutrition. These drivers, often amplified by poverty and inequality, put significant pressure on agrifood systems. The war in Ukraine exemplifies how such dynamics can lead to serious economic consequences for agricultural input costs, as well as global food and energy prices. Additionally, ongoing Israel-Palestine conflict, further contributes to both acute and chronic food insecurity with widespread regional and international complications.

FAO describes food security as “Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life” (FAO, 2001). Climate change affects all dimensions of food security—availability, access, utilization, and stability. However, food availability being particularly sensitive to climate variability due to its direct dependence on crops, livestock, fisheries, aquaculture, and forest products. Increased pests and diseases due to climate change can further reduce both the quality and the quantity of available food, even food, while also adversely affecting food utilization by compromising nutritional value and food safety. Food safety may also be compromised by poor hygiene conditions in food preparation under fresh-water shortages.

Climate variability have a direct implication on food-production system stability. Increased frequency and intensity of extreme events such as drought and flood poses a great threat to food market stability, with widespread regional and international complications. Emergency in food crises due to increased competition for limited resources, resulting in complex transboundary issues such as political conflicts and climate migration and refugees.

Climate-induced hazards escalate socioeconomic and health vulnerabilities globally. Coastal communities face floods and storms, agricultural communities are affected by droughts, and urban populations are increasingly exposed to extreme heat. These impacts result in deaths and injuries, higher risks of respiratory and cardiovascular diseases, the spread of infectious diseases, child malnutrition, premature mortality, and adverse mental health outcomes.

A critical issue is the extent to which agricultural production systems and food systems can deliver mitigation outcomes for these multifaceted climate change vulnerabilities while maintaining food and nutrition security. It is also noted that emission reductions at one phase of the agrifood supply value chain may be accumulated in other phases. For example, shorter food chains can lower transport emissions but may increase emissions from agricultural production, depending on production efficiency. The effectiveness of mitigation measures, therefore, varies by country context and level of development. As a result, efforts to reduce greenhouse gas emissions in agriculture need to adopt a holistic food-value-chain perspective considering interactions with other land use changes.

There is an increasing need for sustainable agricultural production that can satisfy the global demand for food, feed and other agricultural products. Adoption of diversified farming systems is a key element of sustainability in agricultural production systems. Recent analysis (Kamau et al., 2023) indicates that diversified farming systems tend to be more profitable and feasible in the Global North, largely due to well-developed infrastructure, established markets, and price premiums for certified products such as “sustainable” or “organic.” In the Global South, higher suitability is more often observed near major urban centers, where access to infrastructure—such as roads, electricity, and information and communication technologies—supports market access and farm profitability.

Building climate resilience through sustainable agriculture is especially critical for farmers in developing countries, where food insecurity risks are high and policy and financial support are limited. Although climate finance requires significant initial investment, it can strengthen food security while generating global mitigation benefits.

CONCLUSIONS

The agricultural sector faces a dual challenge of meeting the world's increasing food demand while reducing the impacts on ecosystems to mitigate climate change. Yet, shifting diets in many parts of the world are only increasing demand for resource-intensive foods.

Unsustainable agricultural and food production practises is getting massive attention due to growing understanding of cascading detrimental impacts. Specifically, by exacerbating climate change, accounting for up to 40 % of anthropogenic greenhouse gas emissions; the contribution to habitat degradation and biodiversity loss; air, water and soil pollution and the role in driving the emergence and/or spread of disease.

Current agricultural systems are under-equipped to simultaneously meet rising food demand and to mitigate climate change. Predominant agricultural practices are highly vulnerable climate change, while also driving habitat degradation, biodiversity loss, inadequate diets, greenhouse gas emissions, and weakened long-term sustainability.

Agricultural production and food systems need significant transformation to address sustainability, food security, and climate change in an integrated manner. Strengthening climate resilience is essential to enable agricultural communities to manage increasing risks and uncertainty associated with changing climatic conditions.

Climate-smart agriculture and diversified farming systems offer promising pathways to make agricultural sectors more productive, sustainable, and resilient to climate change. Achieving this transition in agrifood systems requires coherent policies, strong institutions, and adequate financing at local, national, and international levels.

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CHAPTER 8

AN ANALYSIS OF CHANGES IN SUGAR BEET PRODUCTION AND FOREIGN TRADE IN TURKEY

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INTRODUCTION

As an industrial crop, sugar beets are primarily used for sugar production, but they are also utilized in the production of molasses, alcohol, yeast, and bioethanol. Sugar is an indispensable source of energy in nutrition. Of the two plants cultivated worldwide for sugar production, sugarcane has higher 2023 planting (respectively, 27,028,428 ha, 202,579,746.5 tons, 74,951 kg ha^{-1}), production, and yield values than sugar beet (4520200 ha, 281194639 ton, 62209 kg ha^{-1}) (FAOSTAT, 2025). However, in Turkey, the 2024 planting, production, and yield values (respectively, 5.2 ha, 352 ton, 74.951 kg ha^{-1}) for sugarcane are significantly lower than those for sugar beet (329092 ha, 22413967 ton, 68.310 kg ha^{-1}) (Table 1).

Table 1. World and Turkey Sugar Beet and Sugar Cane Planting Values

		Cultivated area (ha)	Production quantity (ton)	Yield (kg ha^{-1})
Sugarbeet	World	4.520.200	281.194.639	62.209
	Türkiye*	329.092	22.413.967	68.310
Sugarcane	World	27.028.428	2.025.797.465	74.951
	Türkiye*	5.2	352	67692

Source: World 2023 values FAOSTAT (2025), * Turkey 2024 values TÜİK (2025a)

As of 2024, the total cultivated agricultural area in Turkey is 24.02 million hectares, of which 18.37 million hectares are used for cereals and other plant products. The sugar beet cultivation area corresponds to 17.92% of the total cultivation area for cereals and other plant products (TÜİK 2025b).

This study aims to examine the changes in sugar beet and, to a lesser extent, sugarcane planting, production, yield, and import values over a twenty-one-year period, from 2004 to 2024, as provided by the Turkish Statistical Institute (TÜİK) Statistical Data Portal.

MATERIALS AND METHOD

The data used in this study were obtained from the Turkish Statistical Institute (TÜİK) (Plant Production and Foreign Trade Statistics) and the Food and Agriculture Organization (FAO) (United Nations Food and Agriculture Organization) statistics. The aim was to examine the changes in sugar beet production and imports over the last 21 years, from 2004 to 2024. Area indices for planting area, production volume, and yield values were calculated; trend graphs for planting area, production volume, yield values, imports, and exports were obtained. **The 2004 value index was set at 100**. Figure 1 shows an image of the sugar beet harvest created using artificial intelligence.

Figure 1. View of sugar beet harvest (generated by Google Gemini)

THE STATE OF SUGAR BEET PRODUCTİON İN TURKEY

Changes in Sugar Beet Cultivation Areas in Turkey Over the Past 21 Years

Looking at the data for sugar beet cultivation areas over the last 21 years, the cultivation area in Turkey was 3,153,440 da in 2004, 3,256,995 da in 2007, and 2,972, 648, 2,806,945, 2,913,282, 2,887,851, 2,744,873 da), 2018-19 (2,921,044, 3,137,891 da), 2021-22 (3,054,051, 2,975,096), while they decreased in the 2005-6 (3,358,120, 3,256,995), 2008-10 (3,219,806, 3,244, 428, 3,291,669 ha), 2016-17 (3,224,477, 3,392,742 ha), 2020, 2023-24 (3,640,696, 3,290,923 ha) periods. The highest planting area in the last 21 years was 3,640,696 da in 2023. However, compared to 2023, it decreased by 9.61% in 2024 to 3,290,923 da (Table 2).

Table 2. Changes in sugar beet cultivation areas in Turkey (2004-2024)

Years	Sugar Beet Cultivated Area (da)	Area İndex (2004= 100)
2004	3.153.440	100,00
2005	3.358.120	106,49
2006	3.256.995	103,28
2007	3.002.421	95,21
2008	3.219.806	102,10
2009	3.244.428	102,89
2010	3.291.669	104,38
2011	2.972.648	94,27
2012	2.806.945	89,01
2013	2.913.282	92,38
2014	2.887.851	91,58
2015	2.744.873	87,04
2016	3.224.477	102,25
2017	3.392.742	107,59
2018	2.921.044	92,63
2019	3.137.891	99,51
2020	3.381.078	107,22
2021	3.054.051	96,85
2022	2.975.096	94,34
2023	3.640.696	115,45
2024	3.290.923	104,36

Source: Turkish Statistical Institute, 2025a

When considering the data, a fluctuating trend in planting area is observed over the past 21 years, with 2004 as the base year. The lowest planting area of 2,744,873 hectares was recorded in 2015, An upward trend was observed in 2005, 2010, 2017, 2020, and 2023, but overall, there has been a slight increase in the sugar beet planting area in Turkey (Figure 2).

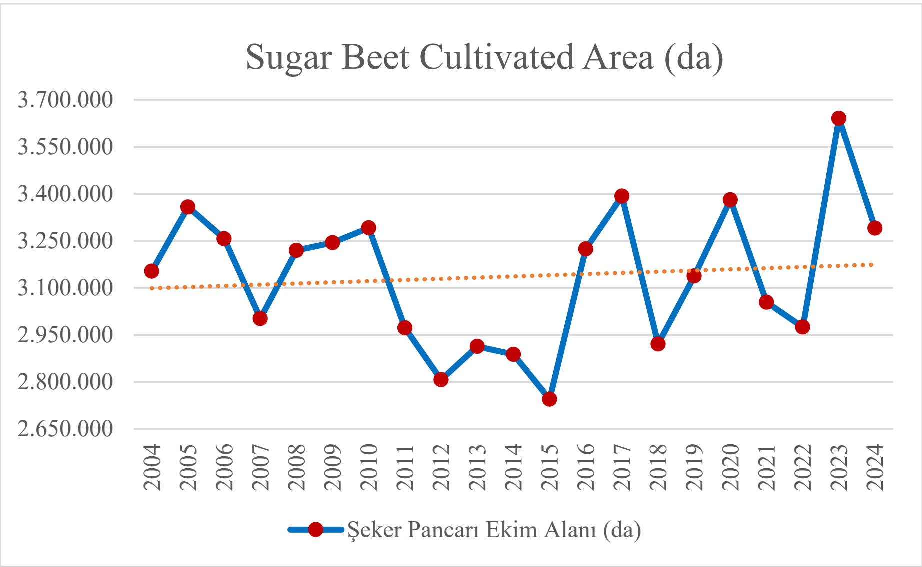

Figure 2. Changes in sugar beet cultivation area in Turkey, 2004–2024 (Turkish Statistical Institute, 2025a).

Changes in Sugar Beet Production Quantities in Turkey Over the Last 21 Years

Changes in Sugar Beet Yields in Turkey Over the Past 21 Years

When examining sugar beet yield values in Turkey over the last 21 years, the average sugar beet yield was 4,290 kg da-1 in 2004. However, there was a decline to 5,154 kg da-1 in 2007, representing a decrease of 3.17%, while increases were observed in all other years. In particular, there was an average increase of around 56% in 2017, 2022, 2024, 2020 and 2024 (145.48, 151.93, 159.23, 159.58 and 162.24 kg da-1, respectively) (Table 4).

Table 4. Changes in sugar beet yield in Turkey (2004–2024)

Years	Sugarbeet Yield (kg da^{-1})	Yield İndex (2004= 100)
2004	4.290	100,00
2005	4.524	105,45
2006	4.464	104,06
2007	4.154	96,83
2008	4.829	112,56
2009	5.332	124,29
2010	5.459	127,25
2011	5.488	127,93
2012	5.325	124,13
2013	5.668	132,12
2014	5.824	135,76
2015	5.848	136,32
2016	6.086	141,86
2017	6.241	145,48
2018	5.998	139,81
2019	5.822	135,71
2020	6.846	159,58
2021	5.876	136,97
2022	6.518	151,93
2023	6.960	162,24
2024	6.831	159,23

Source: TÜİK, 2025a

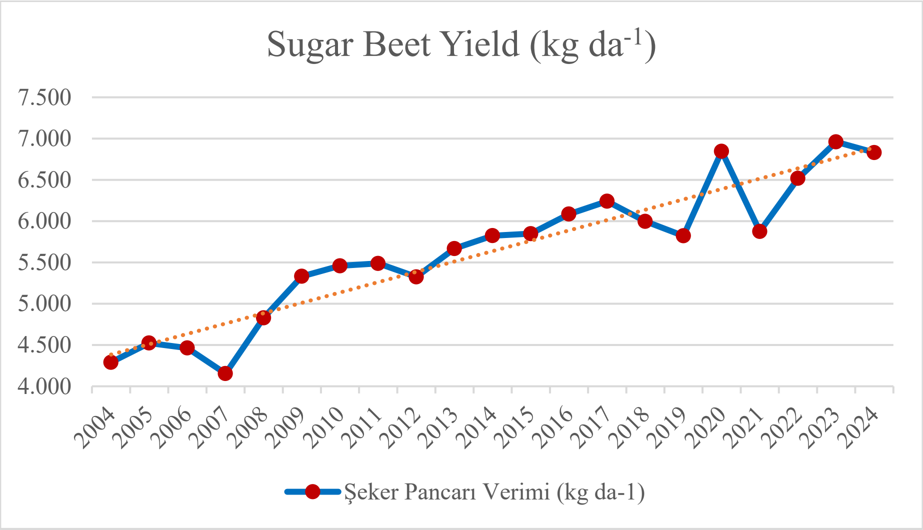

Figure 4. Changes in sugar beet yield in Türkiye, 2004-2024 (TÜİK, 2025a)

As shown in Figure 4, when looking at the average yield values of sugar beets, sugar beet yields gradually increased in all years except 2007, based on the 2004 period.

Provinces with the Largest Sugar Beet Planting Areas in Turkey in 2024: Production and Yield Status

When examining the sugar beet planting area, production, and yield figures for Turkey in 2024, sugar beet farming is practiced in 59 provinces across Turkey.

According to 2024 data, Turkey has reached a production of 22,412,967 tons with a planting area of 3,290,923 decares. Konya has the largest share in planting area with a rate of 26.46% and in production with a rate of 31.83%. After Konya, the provinces producing over 1 million tons are Eskişehir with 6.53%, Yozgat with 6.43%, Sivas with 4.62%, Afyonkarahisar with 4.76%, Kayseri with 5.55%, and Aksaray with 5.36%. These provinces account for 65.08% of Turkey's sugar beet production.

Turkey's top 15 provinces in terms of sugar beet cultivation area (3,290,923 da) are: Konya with 26.46%, Eskişehir with 7.49%, Yozgat with 5.66%, Sivas with 5.53%, Afyonkarahisar with 4.81%, Kayseri with 4.56%, Aksaray with 4.49%, 3.72% in Ankara, 3.24% in Muş, 2.44% in Amasya, 2.43% in Tokat, 2.12% in Çorum, 2.00% in Kahramanmaraş, 1.93% in Kütahya, and 1.92% in Karaman. (Table 5).

Table 5. Provinces where sugar beet cultivation took place in Turkey in 2024

Ranking	Provinces	Cultivated Area (da)	Production quantity (ton)	Yield (kg da^{-1})
1	Konya	870.754	7.133.384	8.197
2	Eskişehir	246.467	1.463.085	5.962
3	Yozgat	186.289	1.440.216	7.744
4	Sivas	181.976	1.035.924	5.700
5	Afyonkarahisar	158.199	1.067.193	6.746
6	Kayseri	149.996	1.244.840	8.342
7	Aksaray	147.611	1.202.148	8.145
8	Ankara	122.308	705.029	5.764
9	Muş	106.707	645.768	6.052
10	Amasya	80.224	378.099	4.904
11	Tokat	80.047	517.907	6.501
12	Çorum	69.856	430.883	6.169
13	Kahramanmaraş	65.834	384.799	5.845
14	Kütahya	63.503	364.344	5.737
15	Karaman	63.050	527.089	8.360
16	Nevşehir	58.139	391.153	6.728
17	Erzincan	50.623	288.772	5.733
18	Ağrı	49.800	211.792	4.253
19	Kırşehir	45.123	278.056	6.162
20	Kastamonu	44.237	198.372	4.525
21	Burdur	37.887	214.186	5.653
22	Bayburt	34.286	146.701	4.279
23	Elazığ	33.544	206.660	6.161
24	Bitlis	32.768	172.460	5.350
Ranking	Provinces	Cultivated Area (da)	Production quantity (ton)	Yield (kg da^{-1})
25	Samsun	29.454	138.401	4.778
26	Antalya	27.718	144.058	5.197
27	Denizli	26.763	157.631	5.890
28	Erzurum	23.232	103.535	4.457
29	Kars	21.160	120.407	5.690

30	Isparta	20.675	115.242	5.577
31	Gümüşhane	17.430	82.241	4.718
32	Niğde	16.417	97.179	5.919
33	Gaziantep	13.320	101.894	7.650
34	Kırıkkale	12.819	80.296	6.264
35	Van	12.307	64.310	5.375
36	Edirne	11.207	59.707	5.366
37	Sakarya	10.058	62.862	6.250
38	Malatya	8.204	46.759	5.700
39	Diyarbakır	7.862	42.343	5.386
40	Kırklareli	7.772	65.372	8.619
41	Şanlıurfa	7.329	59.087	9.182
42	Tekirdağ	6.814	38.782	5.791
43	Çankırı	6.288	27.227	4.330
44	Uşak	5.955	38.348	6.440
45	Bursa	5.492	39.846	7.255
46	Adana	4.389	34.402	7.838
47	Çanakkale	3.205	19.568	6.105
48	Sinop	1.453	6.554	4.511
49	Bilecik	1.151	6.665	5.791
50	Balıkesir	668	2.478	4.172
51	Iğdır	650	2.469	3.798
52	Düzce	403	1.558	3.866
53	Muğla	400	1.157	2.893
54	Adıyaman	371	1.861	7.023
55	Tunceli	320	1.414	4.419
56	Manisa	162	847	5.228
57	İzmir	133	229	1.722
58	Bolu	68	77	1.132
59	Kocaeli	46	301	6.543
	TÜRKİYE	3.290.923	22.413.967	6.831

Source: TÜİK, 2025a

As shown in Table 5, when comparing average cotton yields in 2024, Şanlıurfa ranks first with 9182 kg da^{-1}, Kırklareli ranks second with 8619 kg da^{-1}, Karaman ranks third with 8360 kg da^{-1}, Kayseri ranks fourth with 8342 kg da^{-1}, Konya ranks fifth with 8,197 kg da^{-1}, and Aksaray ranks sixth with 8,145 kg da^{-1}.

SUGAR BEET AND SUGAR CANE TRADE IN TURKEY

Table 6. Turkey's sugar beet foreign trade (2004-2024)

Years	Import Quantity (tons)	Import Value (1000 dollars)	Export Quantity (tons)	Export Value (1000 dollars)
2004	56686,00	2651,00	0,00	0,00
2005	18900,00	1445,00	0,00	0,00
2006	66611,00	3537,00	0,00	0,00
2007	14500,00	1045,00	2,00	0,00
2008-2011	0,00	0,00	0,00	0,00
2012	0,00	0,00	1,00	2,00
2013	0,00	0,00	0,00	0,00
2014	0,00	0,00	0,66	1,00
2015	0,00	0,00	0,00	0,00
2016	0,00	0,00	0,11	0,00
2017	0,00	0,00	0,06	0,00
2018	0,00	0,00	0,00	0,00
2019	0,00	0,00	0,11	0,00
2020	0,00	0,00	2,30	0,00
2021	0,00	0,00	7,85	33,00
2022	0,22	1,00	3,19	20,00
2023	1,27	2,00	94,86	15,00
2024	0,00	0,00	0,30	4,00

Source: FAOSTAT, 2025

Considering Turkey's twenty-one-year sugar beet foreign trade data; while the import volume was 56,686 tons in 2004, it decreased by 66.65% to 18,900 tons in 2005 and increased by 17.51% to 66,611 tons in 2006. and in 2007, it decreased by 74.42% to 14,500 tons. Until 2024, imports have been zero, except for 0.22 tons in 2022 and 1.27 tons in 2023. In contrast, over the twenty-one-year period, sugar beet imports totaled $8,681,000 (Table 6).

As shown in Table 6, sugar beet export values were 2.00 tons in 2007, 1.00 tons in 2012, 0.66 tons in 2014, 0.11 tons in 2016, 0.06 tons in 2017, 0.11 tons in 2019, 2.30 tons in 2020, 7.85 tons in 2021, 3.19 tons in 2022, 94.86 tons in 2023, and 0.30 tons in 2024, totaling 112.44 tons and $75,000 worth of sugar beet exports over a twenty-one-year period (Table 6).

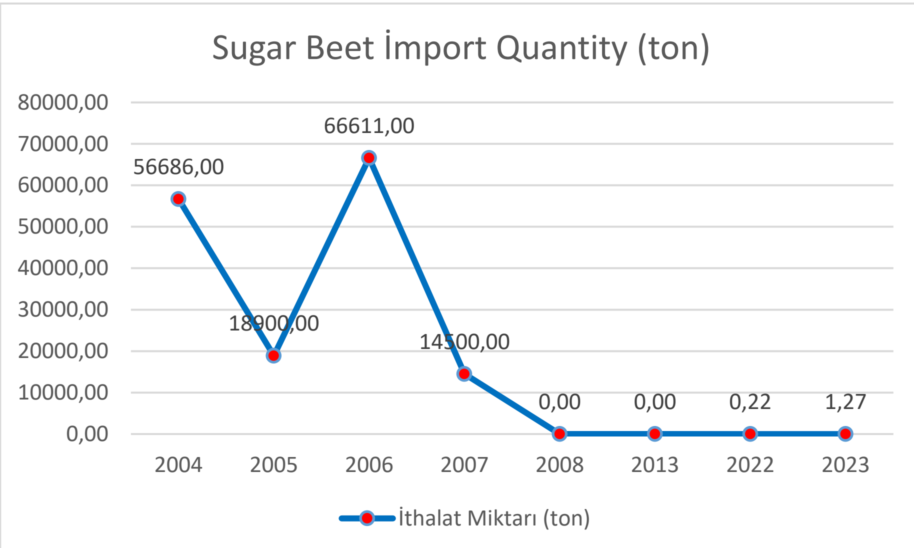

Figure 5. Turkey sugar beet imports (tons)

Source: FAOSTAT, 2025

As shown in Figure 5, sugar beet imports were recorded between 2004 and 2007, but were reduced to zero from 2008 onwards as self-sufficiency was achieved.

Table 7. Turkey's sugarcane foreign trade (2004-2024)

Years	Import Quantity (tonnes)	Import Value (1000 dollars)	Export Quantity (tonnes)	Export Value (1000 dollars)
2004-2013	0,00	0,00	0,00	0,00
2014	1802,40	914,00	948,05	847,00
2015	2865,21	918,00	542,79	600,00
2016	715,75	325,00	1257,61	987,00
2017	3292,19	1053,00	1367,21	1098,00

2018	1633,45	603,00	749,85	685,00
2019	2077,53	802,00	1113,35	1294,00
2020	3549,22	1298,00	903,32	1060,00
2021	2937,62	1477,00	694,83	946,00
2022	2167,34	1023,00	2835,89	4023,00
2023	1810,63	810,00	1772,04	1994,00
2024	283,08	127,00	1218,08	1142,00

Source: FAOSTAT, 2025

Table 7 also provides Turkey's sugar cane export and import values for the last twenty years. As can be seen from the table, apart from 2004-2013, between 2014 and 2024, 23,134.42 tonnes were imported, and the equivalent of 9,350,000 dollars was paid in foreign currency. In contrast, 13,403.02 tonnes were exported, generating 14,676,000 dollars in foreign exchange revenue.

Table 8. Sugar beet product balance sheet (supply and use (tonnes) and sufficiency rate (per cent))

Years	Available Production (tonnes)	Imports (tonnes)	Supply (ton)	Processed Section (ton)	Losses (tons)	Domestic Use (tons)	Exports (tons)	Usage (ton)	Competency level (%)
2000	18758933	38149	18797082	17605000	1191738	18796738	344	18797082	99,8
2001	12550670	24444	12575114	11962000	613114	12575114	0	12575114	99,8
2002	16523167	87462	16610629	15609700	1000929	16610629	0	16610629	99,5
2003	12758383	56686	12815069	12309000	506069	12815069	0	12815069	99,6
2004	13752709	0	13752709	13259200	493509	13752709	0	13752709	100
2005	15181250	64511	15245761	14657050	588711	15245761	0	15245761	99,6
2006	14452162	21000	14473162	13743812	729350	14473162	0	14473162	99,9
2007	12414715	14500	12429215	12121666	307547	12429213	2	12429215	99,9
2008	15488332	0	15488332	15182384	305948	15488332	0	15488332	100
2009	17274674	0	17274674	16981939	292735	17274674	0	17274674	100
2010	17942112	0	17942112	17260776	681336	17942112	0	17942112	100
2011	16126489	0	16126489	15641511	484969	16126480	9	16126489	100
2012	14919940	0	14919940	14515831	404109	14919940	0	14919940	100
2013	16488590	0	16488590	16036402	452188	16488590	0	16488590	100
2014	16743045	0	16743045	16188752	554292	16743044	1	16743045	100

2015	16022783	0	16022783		15418923	603860	16022783	0	16022783		100
2016	19592731	0	19592731		18715614	877117	19592731	0	19592731		100
2017	21149020	0	21149020		20467586	681434	21149020	0	21149020		100
2018	17436100	0	17436100		17049102	386998	17436100	0	17436100		100
2019	18054320	0	18054320		17751820	302500	18054320	0	18054320		100
2020	23025738	1	23025739		22291911	733822	23025733	6	23025739		100
2021	17767085	16	17767101		17423766	343311	17767077	24	17767101		100
2022	19253962	0	19253962		18858051	395897	19253948	14	19253962		100
2023	25250213	0	25250213		24251403	998716	25250119	94	25250213		100
	a	b	A=a+b		e	f	g	h	K=g+h g=e+f		

Supply=Usage **A=K**

Supply = (production + imports) - production losses
A=a+b

Usage = exports + usage (consumption + seed usage + losses)
K=g+h

Sufficiency Rate = (Domestic Production / Domestic Consumption) * 100
Y=((a-c)/g)*100

TÜİK, 2025a

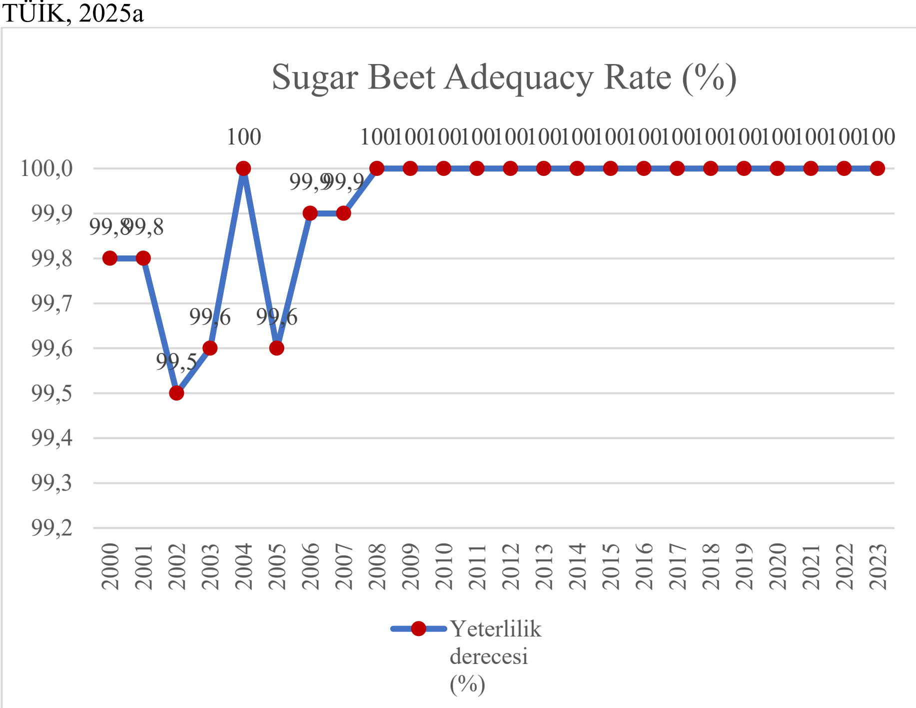

Figure 5. Turkey's sugar beet self-sufficiency rate, 2004-2024

Source: TÜİK, 2025a

Looking at the sugar beet values in Turkey's twenty-four-year (2000-2023) crop balance table, it can be seen that it has had 100% self-sufficiency over the years (Table 8, Figure 6).

CONCLUSION AND RECOMMENDATIONS

Under Turkish conditions, sugar beet production is cultivated and consumed for industrial use to obtain sugar.

According to TÜİK data, Turkey's self-sufficiency rate for sugar beet was 100% as of 2023.

However, sugarcane farming has also seen a start in the last 11 years, but while sugarcane production in 2024 was 352 tons, sugar beet production was 22,413,967 tons, which is 6.4 million tons more than the aforementioned value.

In general terms, Turkey's sugar beet cultivation reached its highest **planting area** in 21 years in 2023, with 3,640,696 da. However, in 2024, it decreased by 9.61% compared to 2023, falling to 3,290,923 da. The **production volume** of sugar beet was 13,517,241 tons in 2004, declining by only 8.6% to 12,414,715 tons in 2007, while increasing in all other years, reaching 22,413,967 tons in 2024. When examining sugar beet **yield values**, based on the 2004 period, the average sugar beet yield was 4290 kg da^{-1}, while in 2007 alone, there was a 3.17% decrease to 5154 kg da^{-1}. other than that, an increase was observed in all other years, and this value rose to 6831 kg da^{-1} in 2024.

The presentation of data in this study on sugar beet, which can contribute to agriculture through yield-focused research in production, will also shed light on future evaluations.

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CHAPTER 9

MICROBIOME-ASSISTED PLANT PROTECTION IN MEDICINAL AND AROMATIC PLANTS: USE OF PLANT PROBIOTICS AND BIOCONTROL STRATEGIES

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INTRODUCTION

1. Introduction to the microbiome-assisted plant protection approach

Medicinal and aromatic plants (MAPs) are indispensable raw materials for the pharmaceutical, food, cosmetic, and aromatherapy sectors, and are a special group of plants with increasing economic value worldwide (Açıkgöz 2025; Açıkgöz et al. 2025). The essential oils and secondary metabolites derived from these plants not only form the basis of industrial products but also have potential as natural biopesticides (Chaves et al. 2025; Tugume et al. 2025). However, MAP production systems face numerous agronomic challenges, including susceptibility to pathogens, soil fatigue, risk of pesticide residues, and low tolerance to biotic stresses.

The phytochemical richness of medicinal and aromatic plants has made them both targets and potential sources of resistance for pests and pathogens. While secondary metabolites such as essential oils, phenolic compounds, alkaloids, and terpenoids can provide a natural defense against some pathogens, this protection is not sufficient for all species and environmental conditions (Greff et al. 2023). However, because the production of these compounds varies depending on genetics, environmental factors, and microbial interactions, the development of sustainable protection strategies for medicinal plants is of particular importance.

At this point, microorganisms that live symbiotically with plants, especially bacteria originating in the rhizosphere and endosphere play important roles in increasing the resilience of medicinal plants to both biotic and abiotic stress conditions. Beneficial bacterial species such as *Bacillus subtilis*, *Pseudomonas fluorescens* and *Azospirillum brasilense* colonize the root zone, preventing pathogen penetration, triggering systemic resistance responses, and even enhancing the synthesis of some secondary metabolites (Castronovo et al. 2021). These microorganisms not only protect the plant but can also directly influence the qualitative and quantitative properties of essential oil components. These beneficial microorganisms, called plant probiotics, exhibit growth-promoting effects when applied to the root systems of medicinal plants while also limiting the proliferation of various phytopathogens through biological mechanisms. Mechanisms include antibiotic production, iron competition via siderophore synthesis, enzymatic activity (e.g., chitinase, β-glucanase) that weakens pathogen walls, and micro population suppression (Sharma and Lee 2025). These properties reduce reliance on conventional pesticides and make them compatible with organic production systems. Another advantage of these microbial agents used in medicinal plants is their contribution to essential oil productivity and quality. For example, *Ocimum basilicum* (basil) plants inoculated with *Trichoderma harzianum* showed significant increases in both biomass and the content of key components such as linalool (Weisany et al. 2023). Similarly, Lavandula angustifolia plants treated with *Bacillus* spp. strains experienced shorter flowering times and a balanced increase in essential oil content. These findings demonstrate that bioprotection and quality improvement goals can be achieved simultaneously. However, although microbiome-based protection systems appear environmentally friendly and effective, they present challenges in practical applications. Factors such as the environmental stability of microbial inoculants, the compatibility of the target plant species' microbiome, and the carrier material directly impact success rates (Gupta et al. 2023). Furthermore, in some cases, microbial agents may have a limited duration of action, requiring repeated applications. Therefore, research on microbial mixtures (consortia) adaptable to field conditions and tested across different species is gaining increasing importance.

In recent years, research on environmentally friendly plant protection strategies in MAP cultivation has increased, and in this context, the benefits provided by the plant microbiome have begun to attract attention. The microbiome encompasses the bacterial, fungal, and archaeal communities naturally found in the rhizosphere, endosphere, and phyllosphere of plants and has a direct impact on plant development, disease tolerance, and stress resistance (Castronovo et al. 2021). Beneficial microorganisms, particularly *Bacillus*, *Pseudomonas*, *Trichoderma*, and *Azospirillum*, are recommended as "plant probiotics" due to their growth-promoting (PGPR) and pathogen-suppressing effects (Sharma and Lee 2025).

A microbiome-based bio protection approach in medicinal plants not only reduces the environmental and health risks of traditional pesticide use but can also positively impact essential oil and secondary metabolite production (Gupta et al. 2023). Studies on aromatic plants, particularly Mentha spicata, have reported that *Trichoderma asperellum* and *Bacillus subtilis* strains both control soil-borne diseases such as root rot and promote plant growth (Castro-Restrepo et al. 2022).

This book chapter examines microbiome-supported plant protection approaches in medicinal and aromatic plants. This study aims to comprehensively demonstrate the effects of plant probiotics, microbial biocontrol agents, endophyte-soil microbial interactions, and microbiome modulation on plant health and crop quality. Comparative analyses with traditional methods and future research recommendations will also be presented.

2. The microbiome of medicinal and aromatic plants

Medicinal and aromatic plants (MAPs) hold an important place not only in the food and cosmetic industries but also in traditional and modern medicine due to their metabolite diversity and economic value.

The phytochemical productivity of these plants is directly influenced by genetic factors as well as their interactions with microorganisms (Sun et al. 2025). The plant root environment (rhizosphere), internal tissues (endosphere), and leaf surface (phyllosphere) are microecosystems where MAPs are in constant interaction with dynamic microbial communities (Xu et al. 2023; Regvar et al. 2025).

These microbiomes play a role in numerous vital functions, ranging from plant nutrient uptake and resistance to phytopathogens to secondary metabolite synthesis and environmental stress tolerance (Hossain et al. 2025; Mohanan et al. 2025). Rhizobacteria and endophytes can secrete hormones that promote plant growth, activate systemic resistance responses, and competitively inhibit the establishment of pathogens (Varghese et al. 2025; Li et al. 2025). Thanks to these features, microbiome-based protection systems have become an environmentally friendly alternative to conventional pesticide use. Siderophores, antibiotics, and hydrolytic enzymes produced by beneficial microorganisms in the rhizosphere particularly species known as PGPR (Plant Growth Promoting Rhizobacteria) inhibit the proliferation of harmful microorganisms in the root zone. For example, *Pseudomonas putida* and *Bacillus amyloliquefaciens* are among the primary species reported in the literature to exhibit bioprotective effects in MAPs (Lawal et al. 2025; Potisap et al. 2025). These microorganisms also improve nutrient use efficiency by increasing phosphorus solubility (Khan et al. 2024).

Endophytic microorganisms are species that can survive asymptomatically in the root, stem, and leaf tissues of MAPs (Haidar et al. 2025). Mycorrhizal endophytes, particularly *Piriformospora indica* and *Serendipita* spp., have shown positive effects on plant health, including increased essential oil content and stress resistance (Dagher et al. 2025). As a result of these interactions, secondary metabolite synthesis and quality parameters are enhanced, while plant tolerance levels under pathogen pressure also increase (Khan et al. 2025).

Metagenomics have revealed a high diversity of microbial communities within MAPs. Bacterial and fungal species have been shown to exhibit both specific and habitat-specific distributions in common aromatic plants such as *Ocimum*, *Mentha*, *Lavandula*, and *Thymus* (Semenzato and Fani 2024). This diversity can affect the bioactivity of plant-derived metabolites and can be controlled through microbiome engineering applications (Bose et al. 2022). The role of microbiomes in secondary metabolite production is important not only for yield but also for product standardization. Studies show that the number of essential oils and the diversity of bioactive compounds increase significantly in production systems enriched with probiotic microorganisms (Açıkgöz 2020). For example, a microbial consortium applied to *Lavandula angustifolia* increased the levels of linalool and lavandulol, providing therapeutic value (Leong et al. 2021).

In conclusion, the microbiome of medicinal and aromatic plants is not merely a passive ecological partnership but rather a functional biological entity that actively suppresses phytopathogens, confers stress resistance, and improves product quality. More effective use and management of this microbial entity in sustainable agriculture practices; It is indispensable for obtaining environmentally friendly, high quality and high economic value products.

3. Plant probiotics and their mechanisms of action

Plant probiotics is a term used to describe beneficial microbial strains that support healthy plant development, increase stress tolerance, and enhance resistance to harmful microorganisms. These microorganisms can naturally occur in the plant's root zone (rhizosphere), leaf surface (phyllosphere), or internal tissues (endosphere). Efforts to reduce synthetic inputs in modern agriculture have made these microorganisms biological agents of sustainable agriculture (Guzmán-Guzmán et al. 2025; Riseh et al. 2025; Xiang et al. 2025).

Key plant probiotics include PGPR (Plant Growth-Promoting Rhizobacteria) and endophytic bacteria and fungi. Common examples include microorganisms such as *Bacillus* spp., *Pseudomonas* spp., *Azospirillum* spp., *Rhizobium* spp. and *Trichoderma* spp. (Majhi et al. 2025; Saikia et al. 2025; Sandhu et al. 2025). These microorganisms can suppress phytopathogens and regulate metabolite synthesis by creating multifaceted effects on the plant through direct or indirect means.

The biocontrol mechanisms of plant probiotics are multi-layered:

They inhibit target pathogens through antibiotic production.

They limit pathogen growth by binding micronutrients such as iron through siderophore synthesis.

They act by degrading fungal cell walls with hydrolytic enzymes (chitinase, β-glucanase) (Marcianò et al. 2025; Moon et al. 2025; Yao et al. 2025).

They cover the root surface through competitive colonization, preventing pathogens from establishing themselves (Riseh et al. 2025; Tsai et al. 2025).

In addition, these microorganisms can directly activate the plant immune system. Defense pathways such as Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR) are activated because of these interactions (Jawadayn et al. 2025). ISR generally operates through jasmonate and ethylene signaling, while SAR is more commonly activated through salicylic acid (Roychowdhury et al. 2025; Thakur and

Yadav 2025). These mechanisms make it more difficult for pathogens to harm the plant. Some plant probiotics are also active in phytohormone production. Hormones, particularly indole-3-acetic acid (IAA), gibberellins, and cytokines, directly stimulate plant growth. This provides both bio protection and positive impacts secondary metabolite synthesis (Giri et al. 2025; Kućko et al. 2025). For example, significant increases in both biomass and essential oil yield have been reported in *Ocimum basilicum* plants inoculated with *Azospirillum brasilense* (Oliveira et al. 2025; Papaianni et al. 2025; Wilches-Ortiz et al. 2025).

Plant probiotics have diverse agricultural applications: they can be applied through methods such as seed coating, seedling dipping, and drip inoculation (Kumar et al. 2025; Ma et al. 2025). They offer practical and cost-effective solutions that can be integrated into both organic and conventional production systems, particularly in medicinal plants. Furthermore, microbial consortia composed of multiple strains exhibit synergistic effects, providing stronger and longer lasting bio protection (Renganathan et al. 2025; Singh et al. 2025).

4. The effect of the microbiome on essential oil composition and yield

Medicinal and aromatic plants (MAPs) have a wide range of uses, from traditional therapeutic systems to the pharmaceutical industry, thanks to their potential for producing natural compounds. Secondary metabolites, particularly essential oils, largely determine the efficacy and economic value of these plants (Açıkgöz 2020). Recent scientific research has revealed that essential oil synthesis varies not only depending on the plant's genetic makeup or environmental conditions (Açıkgöz et al. 2025), but also on the microbial communities interacting with the plant, the microbiome. Microbiomes consist of mostly symbiotic microorganisms that live in the rhizosphere, endosphere, and phyllosphere of the plant, with either beneficial or neutral effects (Peng et al. 2025). The microbiome's impact on the plant is far more comprehensive than classical growth promotion; it can directly influence the plant's defense system, nutrient uptake capacity, stress tolerance, and, most importantly, the secondary metabolite profile (Singh et al. 2025). In this context, the evidence that a significant portion of the observed variation in essential oil quantity and composition is due to microbial interactions is growing stronger (Ramekar and Dutt 2025). The microbiome's influence on essential oil composition is largely mediated through regulation of molecular signaling pathways, hormone production, nutrient bioavailability, and gene expression. Rhizobacteria and endophytic microorganisms synthesize phytohormones, particularly indole-3-acetic acid (IAA), gibberellin, and cytokinin, activating metabolic processes necessary for secondary metabolite production in the plant (Al Raish et al. 2025). They also facilitate more efficient plant uptake of micronutrients such as iron through siderophore production. Consequently, terpenoid pathways contributing to essential oil biosynthesis are activated. Metagenomic analysis by Ezaouine et al. (2025), one of the studies investigating the molecular mechanisms of these mechanisms, revealed that the rhizosphere microbiota of the *Satureja nepeta* species induces significant changes in the essential oil profile. Statistically significant increases in 1,8-cineole and carvacrol levels were observed, particularly in areas where the *Bacillus* and *Pseudomonas* genera were abundant. This demonstrates that not only the quantity but also the species composition of the microbial community can influence essential oil synthesis.

Microbiome-supported essential oil production becomes particularly pronounced under stress conditions (drought, salinity, heavy metal presence). Under stress conditions, plants generally develop survival strategies to increase secondary metabolite production. During this process, microbiome members modulate this increased production by providing bioactive support to the plant. For example, a study conducted on *Ocimum basilicum* observed a 20 % increase in eugenol and linalool contents in plants inoculated with PGPR (Plant Growth Promoting Rhizobacteria) under water stress (Molkabadi et al. 2023). This increase is significant not only in terms of the amount of the compound but also in terms of the therapeutic quality of the product. Furthermore, these changes in essential oils have become amenable to microbiome engineering. This means that it is possible to develop specific microbial formulations by targeting specific metabolites.

The plant-microbiome interaction directly affects not only yield but also the quality parameters of the essential oil (Compant et al. 2025). Quality is measured by the ratios of major and minor components in essential oil (Su et al. 2023). The ratio of these components determines factors such as therapeutic effect, aroma profile, and stability. In field trials on *Lavandula angustifolia*, linalool content increased by 20 % in samples treated with *Bacillus subtilis*, while improvements were also observed in synergistic components such as linalyl acetate (Crișan et al. 2023). Such improvements are particularly valuable for product standardization for medicinal use. It is understood that microbiomes play a role not only in individual compounds but also in the overall chemical balance of the essential oil. Furthermore, the microbiome's influence on the essential oil can vary from species to species, even in different ecotypes of the same species. Therefore, numerous variables such as location, soil structure, climatic conditions, and microbial diversity must be considered in essential oil production processes (dos Santos et al. 2025).

It is also important to evaluate the effects of microbiomes on essential oil production in the context of sustainable agriculture (Compant et al. 2025). Synthetic chemicals used for plant protection pose significant risks to both environmental health and product quality (Zhou et al. 2025). In contrast, microbiome-based practices offer an environmentally friendly production model, reducing pest pressure and supporting metabolite synthesis (Al Darwish et al. 2025). For example, a study on *Thymus vulgaris* showed that *Pseudomonas fluorescens* application increased thymol levels while simultaneously providing protection against fungal pathogens (Sammak et al. 2020). This dual effect demonstrates that the microbiome is not only a growth-promoting factor but also a bioprotective agent. *Consortium practices*, where microbiome components work synergistically with different species, are also highly effective for essential oil production (Weisany et al. 2023). In polymetabolite plants such as *Salvia officinalis*, the combined use of AMF (arbuscular mycorrhizal fungi) and PGPRs increased 1,8-cineole production by 37.6 % (Hassiotis 2018). These findings clearly demonstrate the impact of biodiversity on metabolic output.

In conclusion, the influence of microbiomes on essential oil synthesis in medicinal and aromatic plants is a growing area of research, both theoretically and practically. The findings demonstrate the strategic role of microbiome management for producers seeking to increase essential oil production and standardize quality. The use of microbial formulations in production processes directly impacts not only agricultural output but also the market value of the product. Particularly in controlled production systems (greenhouses, vertical farming, agroecological systems), microbiome manipulation can be a guiding element for establishing the desired phytochemical profile. In the future, the combined use of microbially derived bio stimulants and genetically targeted plant species may enable the maximum optimization of essential oil synthesis. In this regard, metagenomics and metabolomics approaches are indispensable for a more detailed understanding of microbial mechanisms of action. The fact that essential oil is not merely a product, but a tangible outcome of microbial-botanical interactions signals a significant paradigm shift in the redesign of modern agricultural systems.

5. Challenges and formulation requirements of microbial applications in field conditions

While microbiome-based approaches offer great potential in medicinal and aromatic plant (MAP) production, the transition of these biological solutions from laboratory scale to field applications faces numerous technical, environmental, and biological challenges. While microbial inoculants used to increase essential oil, components yield effective results under controlled conditions, achieving the same level of success in open fields is often difficult. This is primarily due to the multi-component, variable, and interactive nature of the natural environment. Many variables, such as soil structure, temperature, moisture, pH, microbial competition, plant variety, and agricultural practices, can limit the activity of microbial inoculants. Competition with existing microbial communities in the soil hinders the adhesion and continued activity of additional beneficial microorganisms in the root zone.

One of the most significant challenges encountered in field applications is the survival and colonization ability of microbial inoculants. Santoyo et al. (2021) reported that some PGPR (plant growth-promoting rhizobacteria) strains, which exhibited colonization rates above 90 % under laboratory conditions, reduced this rate to less than 50 % in the field. This decrease varies depending on the timing of application, environmental stresses, competitive microbial species in the field soil, and the formulation of the inoculants. For example, reduced soil water retention in arid conditions shortens microbial survival, while high temperatures can cause denaturation of microbial proteins. Similarly, saline or alkaline soils can negatively affect microbial cell wall stability, reducing the effectiveness of inoculants (Palanisamy et al.

2025). Specialized formulations are required to maintain the biological activity of living cells under these conditions.

Another fundamental problem is formulation stability. Microbial inoculants are generally offered in liquid, powder, or granular forms. However, each of these forms has advantages and disadvantages in terms of shelf life, ease of transport, applicability, and microbial viability. For example, while liquid formulations offer rapid applicability, they face limitations in widespread use due to their short shelf life and temperature sensitivity. On the other hand, while granular or bio capsule formulations offer longer microbial stability, they are costly to produce, and in some cases, the microbial release rate does not reach the desired level. Khan et al. (2023) examined the effects of different formulations on microbial viability and reported that bio capsule forms provide the best results in terms of both viability and colony formation, but in practice, these formulations are very low in preference by manufacturers. This is a significant factor hindering the widespread adoption of biological products.

Furthermore, the need for species-specific compatibility between microbial inoculants and plants is another critical parameter affecting the success of field applications. Each plant species, even different ecotypes of the same species, can respond to microbial colonization at different levels. This limits the universal applicability of inoculants and necessitates the development of specific microbial mixtures for each crop. For example, a *Bacillus* strain effective on *Mentha arvensis* may not have the same success on *Lavandula angustifolia*. Therefore, it is crucial to match the agroecological conditions in which microbial inoculants were developed with the areas where they will be applied. Applications that fail to achieve this match can lead to both economic losses and a decrease in the reliability of the results.

Another complex issue encountered in the context of field applications is microbial interactions and synergy/antagonism. Because single strains do not exhibit the expected effects in the field, the use of multiple microbial consortia is recommended. However, multiple applications lead to the emergence of new interactions in the system. In some cases, these interactions produce synergistic effects, enhancing plant growth and metabolite production, while in other cases, antagonistic effects can occur, with one strain suppressing another. Therefore, microbial mixtures to be used in the field should be optimized not only at the laboratory level but also through long-term field trials. Furthermore, these trials should be conducted considering different soil types, climatic conditions and plant varieties.

Despite all these challenges, the use of microbial inoculants in medicinal and aromatic plant production is an essential strategy for long-term sustainable, environmentally friendly, and high-quality production. However, for this strategy to be successful, solution-oriented approaches must be developed in the following areas: (1) Optimizing formulations for stability, shelf life, and ease of application; (2) Establishing product-specific consortia based on plant-microbiome matching; (3) Modeling microbial interactions at the system level; and (4) Conducting multi-center, seasonal, and long-term field trials. Furthermore, producer education, regulatory frameworks, and the development of the biological product market are critical steps for disseminating these practices.

In conclusion, the applicability of microbial inoculants in field conditions is not yet a fully resolved area. However, considering scientific advances, biotechnological advancements, and the demands for sustainability in agriculture, each improvement in this area will yield significant gains in terms of both product quality and environmental health.

6. Microbiome engineering and future perspectives

The plant microbiome is beginning to be viewed not only as a passive supporter in nature but also as a manageable biological system. In recent years, microbial interactions that regulate complex metabolite networks, such as essential oil composition, particularly in medicinal and aromatic plants (MAPs), have been strategically redesigned under the banner of "microbiome engineering." Microbiome engineering aims to manipulate plant metabolism in a targeted manner by artificially selecting, designing, and integrating microorganisms that form symbiotic or beneficial relationships with the plant. This approach goes beyond traditional biofertilizer and biopesticides applications and aims to offer more controlled, effective, and customized solutions using synthetic microbial consortia (Seenivasagan and Babalola 2021).

Synthetic microbial consortia (SynComs) consist of microorganisms that do not coexist in natural environments but that, when engineered together, can produce synergistic effects in the plant. These consortia are structured to target multiple biological functions, such as hormone production, nutrient solubilization, gene expression modulation, and stress tolerance, which directly impact essential oil production. For example, a SynCom can include a rhizosphere-solubilizing *Bacillus* strain, along with a *Pseudomonas* strain that activates essential oil biosynthesis genes endophytically within the leaf. Thus, a metabolic orchestration is achieved beyond individual effects. Jia et al. (2016) described a complex engineering process in which such synthetic consortia are designed using metagenomic data and subsequently subjected to both in vitro and in planta validation tests. This process also utilizes advanced biotechnological tools such as AI-assisted modeling and CRISPR-based editing. Microbiome engineering holds groundbreaking potential for optimizing essential oil profiles in medicinal plants. While traditional methods such as selection and environmental factor manipulation are time-consuming and have low predictability, microbial engineering can both increase the proportion of desired compounds (e.g., menthol, linalool, eugenol) and ensure quality standardization. Furthermore, while essential oil synthesis is generally suppressed under stress conditions (drought, salinity, heavy metal accumulation), synthetic microbial consortia can stabilize these production processes. This approach is critical not only for increased yield but also for sustainable product quality. Particularly in organic and ecological farming systems, microbiome engineering holds the potential to achieve both production efficiency and environmental respect simultaneously.

However, this new approach also has some significant limitations. The long-term stability of synthetic consortia in nature, their ability to compete with local microbial communities, and their ability to function without being affected by environmental interactions remains a matter of debate. Furthermore, there is no guarantee that engineered microbial agents will perform similarly across all agroecological conditions. However, advances in fields such as molecular biology, metabolomics, and systems biology suggest that these limitations may be overcome over time. Microbiome engineering also requires a multidisciplinary approach, as it encompasses socioeconomic aspects such as regulatory requirements, safety assessments and consumer acceptance.

In the coming years, microbiome engineering will not only increase essential oil yields in medicinal and aromatic plant production; it will also serve objectives such as targeted production of bioactive compounds, tissue-specific metabolite synthesis, and even the development of disease-preventive essential oil profiles. In this context, the development, marketing, and field testing of plant-specific, species-specific, and even ecotype-specific microbial formulations will become essential. The future of microbiome engineering, combined with synthetic biology, data science and agroecological intelligence, offers a paradigm that will redefine medicinal plant production, one of the most complex areas of agriculture.

7. General assessment and conclusion

Medicinal and aromatic plants (MAPs) have been important natural resources used throughout history in many areas such as treatment, protection, and aromatherapy. One of the most fundamental elements determining the biological and commercial value of these plants is their essential oils. However, the composition and quantity of essential oils are not fixed; they vary significantly depending on environmental stress, genetic makeup, and microenvironmental factors. At this point, microbiomes that interact symbiotically with plants are emerging as a new strategic production tool in modern scientific approaches. Thanks to developing molecular biology techniques, metagenomics, and systems biology, it is now understood that microbiomes not only control growth but also secondary metabolite profiles. Rhizobacteria, endophytic microorganisms, and mycorrhizal fungi have the potential to modulate essential oil production in MAPs.

The studies included in this review demonstrate that with the correct use of microbial inoculants, it is possible to achieve a 20–30 % increase in essential oil yield. Importantly, this increase is not only quantitative; It is also related to quality, that is, changes in the proportions of specific compounds (e.g., linalool, eugenol, menthol). Case studies, particularly on high-economic value species such as *Ocimum*, *Lavandula*, and *Mentha*, have demonstrated that microbial treatments directly impact chemical composition. However, simply selecting the appropriate strain is not sufficient to achieve this effect. It is equally important that the microbial agents are compatible with the plant, resistant to environmental conditions, and presented in an appropriate formulation.

Field applications stand out as the biggest limiting factor in this regard. Microorganisms effective in laboratory environments may not maintain their effectiveness under field conditions due to competition, climatic variability, and environmental stresses. Therefore, inoculants must be transported to the field in stable, applicable, and self-stable formulations. Furthermore, considering the need for plant-specific microbial matching, a "one-size-fits-all" approach will not be applicable in this field. Instead, the development of species-specific, and even ecotype-specific, microbial formulations will increase field success.

The most promising future development is microbiome engineering and the use of synthetic microbial consortia. Microbial mixtures specifically designed for the targeted essential oil compound can now be developed, enabling more predictable, effective, and sustainable production systems. The use of genetic editing techniques such as CRISPR to enhance microbial functions further expands the possibilities in this field. Artificial intelligence systems that can model plant-microbiome interactions offer rapid validation opportunities, reducing the need for field trials.

In conclusion, microbiome-based approaches to optimizing essential oil production in medicinal and aromatic plants emerge as a robust ecological, economic, and functional strategy. However, for this strategy to become effective and widespread, an interdisciplinary perspective is required. Biotechnology, agronomy, microbiology, and pharmaceutical chemistry are integral components of this process. Furthermore, producer education, legal infrastructure, and academic-industry collaborations will form the pillars of this transformation.

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CHAPTER 10

THE EFFECTS OF CHANGING CLIMATE CONDITIONS ON COTTON (*GOSSYPIUM HİRSUTUM* L.) CULTIVATION

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INTRODUCTION

Cotton is a strategically important crop that contributes to poverty reduction in the world's least developed regions. Serving as both a fiber and food source for humans and animals, cotton decomposes more quickly in nature than synthetic alternatives. This plant, which provides employment opportunities for millions of people worldwide, offers annual harvests despite its perennial growth cycle and meets the raw material needs of approximately fifty different industries. Cotton seeds contain 17-24% oil, and after the oil is extracted, the remaining meal contains 40-43% protein, 20-22% nitrogen-free extractives, and 5-8% oil, which is said to add significant value to animal feed formulations (Başbağ et al., 2011).

Cotton fiber is a basic raw material, especially for the textile and apparel industries, while also being a valuable industrial crop used in the energy, animal nutrition, and oil sectors. Of the cotton grown in about eighty countries worldwide, 80% is produced in seven countries, including Turkey. Cotton demand is constantly increasing in line with the development of the apparel and textile industry, which is considered a critical component of industrialization and global market presence in Turkey, with its production capacity, labor force, and exports. Increasing cotton production is of great importance from Turkey's perspective (Özüdoğru, 2021).

The fundamental requirement for high-yielding and successful cotton production begins with the selection of high-quality varieties and continues with the effectiveness of the agricultural practices applied to these varieties. Climatic conditions also play a critical role in achieving the target yield and fiber quality levels of the variety (Esbroeck and Bowman, 1998; Freeland et al., 2006). Yield and fiber quality characteristics emerge as a result of the interaction between all these factors. Research shows that genetic factors account for 48% of the total yield increase, cultivation techniques account for 28%, and the interaction between variety and cultivation technique accounts for 24% (Liu et al., 2013). The effects of certain disruptions in the world's climate conditions are beginning to be seen today. In particular, temperatures above seasonal norms, resulting in drought, irregular rainfall, greenhouse gases, and many other problems are causing serious ecological imbalances and are predicted to continue to pose major risks, especially in terms of agricultural production (Beyyavaş and Cun, 2022). Today, the increasingly noticeable consequences of climate change, such as rising temperatures, changing rainfall patterns, and the increasing number of meteorological disasters each year, are affecting all aspects of human life. Alongside the effects of climate change in various areas such as health, transportation, and trade, the agricultural sector is at the forefront of the areas where the most significant consequences are observed. Although the increase in temperature and rising carbon dioxide concentration resulting from climate change appear to have a positive short-term effect on agricultural yields in some regions, in the long term, these factors can lead to declines in product quality and production volume (Akalın, 2014). Climate change and the resulting increase in meteorological disasters have extremely negative consequences, particularly for agricultural production. According to climate forecasts for the coming periods, significant increases in the frequency and intensity of climate change and its associated negative effects are expected in this century. Climate change will threaten food security and displace people from their settlements. Natural disasters of meteorological origin caused by climate change reduce crop productivity and cause material damage. The resulting damage affects both farming families and the national economy. Given that climate change cannot be reversed in the short term, the most critical measure to be taken will be to adapt to climate change. In this context, adaptation efforts in agriculture against climate change, research examining the potential future impacts of climate change on productivity, and activities such as developing resistant varieties suitable for changing climate conditions are important initiatives that can be taken to prevent future losses (Gürkan et al., 2017).

This study aims to comprehensively examine the effects of climate change on cotton (Gossypium hirsutum L.) production, identify existing problems, and propose solutions for sustainable cotton production. The research aims to analyze changes in the yield and quality parameters of cotton plants under changing climate conditions, to anticipate future challenges, and to determine adaptation strategies that can be developed to address these challenges. Furthermore, recommendations will be made for the development of climate-resilient cotton varieties and the widespread adoption of appropriate agricultural practices to maintain and strengthen Turkey's strategic position in cotton production.

Plant Production Statistics

Global cotton production has followed a fluctuating trend between 2014 and 2023. While cultivation areas ranged between 30 and 34.5 million hectares, cotton fiber production ranged between 22.3 and 25.8 million tons. Yield values ranged between 209.3 and 245.8 kg/da. According to crop production statistics, the highest yield value (245.83 kg/da) was achieved in the 2019 growing season (FAO, 2025). Our country holds an important position in global cotton production. Its share of global cotton planting areas varied between 11.2% and 18.2% during the 2015-2022 growing season. Looking at the 2022 production figures, our country has shown a significant increase, accounting for 18.2% of the world's cotton cultivation area. However, in terms of production share, its share in world cotton fiber production has remained between 2.7% and 4.1%. This situation shows that our country's yield values are below the world average. According to 2023 production data, the provinces with the highest production in Turkey are, in order: Şanlıurfa

(528,610 tons), Diyarbakır (181,884 tons), Aydın (145,639 tons), Hatay (111,002 tons), İzmir (69,060 tons), Adana (51,240 tons), and Manisa (43,297 tons). The Southeast Anatolia Region, particularly Şanlıurfa and Diyarbakır, and the Aegean Region, including Aydın, İzmir, and Manisa, are the centers of cotton production in Turkey. This situation demonstrates the impact of the GAP project on cotton production and the traditional cotton production capacity of the Aegean Region. Cotton yield in Turkey varied between 162.7 and 192.5 kg/da during the 2015-2024 growing seasons. The highest yield was achieved in 2021 at 192.58 kg/da. However, in the 2023 growing season, the yield fell to 162.74 kg/da, reaching the lowest yield value in the last 10 years. When examining the production quantities of provinces that stood out in terms of cotton production during the 2015-2024 cultivation period: Şanlıurfa province followed a fluctuating trend between 340,351 and 661,716 tons. It reached its highest value in 2022, while the lowest production occurred in 2020. Diyarbakır's production, which was 83,641 tons in 2015, increased to 245,032 tons in 2022. Production in Aydın Province fluctuated between 145,639 and 198,696 tons. In recent years, there has been a downward trend in production (TÜİK, 2025).

The Effects of Climate Change on Cotton Production

Although there are many causes of climate change, the increase in greenhouse gases caused by fluorinated gases, CO_2, and many other factors is negatively affecting the world's ecosystems. These negative variables have an adverse effect on ecosystems by changing temperature, rainfall patterns, and seasonal patterns. Climate change is now recognized as an important issue worldwide. Climate change is observed in almost every country, but developing countries are less sensitive to this issue due to their limited capacity to cope with climate change. Another factor is that developing countries are heavily dependent on the agricultural sector. Climate change is generally irregular and has a small global impact. However, geographically, these climate changes can be very serious for some regions or countries. The effects of climate change are seen in most countries in arid and semi-humid regions. Some key factors are that livelihoods depend on agriculture and the lack of financial resources necessary to adopt new technologies. However, it is clear that climate change could seriously damage global food security and have negative effects on the livelihoods of people around the world (Ali et al., 2017). General climate changes have negative effects on plants. Among various environmental changes, temperature and water stress are considered the most important factors. Temperature stress can affect plants during their developmental stages (by affecting the plant's physiological growth) and during maturity or production stages (by affecting fruit development). This can lead to low yields and reduced product quality. Similarly, water stress can potentially harm crop yield in various ways. For example, water stress may reduce yield by affecting pollination and fertilization, while also shrinking leaf area during the vegetative period and closing stomatal openings to reduce water loss (Adhikari et al., 2015). Global warming and climate change cause significant economic losses in the agricultural sector by affecting crop yield and quality (Sharma, 2014).

Heat stress

Cotton (*Gossypium spp.*) is an industrial crop of strategic importance in global agricultural production and exhibits high sensitivity to temperature changes. The effect of air temperature on the cotton plant plays a direct and decisive role in the plant's morphological development, physiological processes, and yield potential. Research in the literature reveals that the dynamic relationship between air temperature and soil temperature is critically important during the development stages of the cotton plant. Soil temperature interacts with various environmental parameters such as plant cover density, soil moisture content, and other edaphic factors (Bolat, 2024). The role of air temperature in determining plant water stress is of great importance in terms of irrigation management in cotton farming. In a study conducted by Ekinci and Başbağ (2019), the effects of air temperature difference and vapor pressure deficit parameters on cotton plants were examined in detail. Continuous monitoring of these parameters is critical, especially for early diagnosis and late-stage determination of water stress. In a study by Erten and Dağdelen (2020), air temperature, vapor pressure deficit, and plant canopy temperature parameters were used to calculate the cotton plant water stress index (CWSI). The findings show that an increase in air temperature increases the soil moisture deficit, resulting in significant reductions in cotton lint yields. This situation reveals that air temperature is a critical determining factor in meeting the plant's water needs. The effects of air temperature were clearly observed in different irrigation regimes applied to cotton plants. The plant water stress index, used to optimize irrigation timing, provides critical information necessary to prevent potential yield losses during periods of high air temperatures (Ekinci & Başbağ, 2019; Erten & Dağdelen, 2020). Such data contributes significantly to the scientific optimization of irrigation strategies in cotton farming. In conclusion, air temperature is a fundamental environmental determinant for cotton plants, and its effects are directly and complexly intertwined with irrigation practices and soil-water balance. The systematic monitoring and evaluation of air temperature changes in cotton production areas is a strategic necessity for ensuring sustainable productivity and plant health.

CO_2 Level

Carbon dioxide (CO_2) concentration, one of the environmental factors affecting the species Gossypium hirsutum L., has significant effects on the plant's growth, development, and yield. CO_2 is one of the main nutrients for plants and is a fundamental component of the photosynthesis process. High CO_2 levels can positively contribute to cotton plant growth by increasing the rate of photosynthesis (Aygün & Mert, 2020; Ödemiş & Candemir, 2023). Many studies have examined the effects of rising CO_2 levels on plant development. In particular, it has been observed that increasing CO_2 improves gas exchange and water use efficiency in cotton plants. The increase in CO_2 concentration reduces transpiration loss by decreasing stomatal aperture, thereby increasing tolerance to water stress (Ödemiş & Candemir, 2023). This situation stands out as a factor that increases the plant's resilience, especially under extreme temperatures and drought conditions. The study by Aydın and Karaca focused on the effects of exposing cotton plants to different CO_2 levels on yield and fiber quality. However, this study did not clearly establish the relationship between CO_2 levels and fiber quality (Aydın & Karaca, 2024). Instead, it mentions the positive effects of CO_2 increase on overall plant health. On the other hand, monitoring CO_2 levels in various agricultural applications, when combined with important factors such as irrigation methods and fertilization strategies, provides valuable information for determining optimal agricultural practices (Saraç et al., 2021). Such strategies are critical for increasing agricultural productivity and supporting sustainable agricultural practices. In conclusion, CO_2 levels have a significant impact on cotton plants, affecting photosynthesis rates, water use efficiency, and ultimately yield. Regular monitoring and optimization of CO_2 levels in cotton-growing regions can contribute to the sustainability of crop production.

Drought stress

Cotton (*Gossypium hirsutum L.*), which is among industrial crops, is severely affected by drought conditions. This situation has negative effects on the plant's growth, yield, and fiber quality. The effects of drought can cause yield losses by directly affecting the plant's irrigation needs and water consumption. Research shows that drought stress negatively affects the morphological and physiological characteristics of the cotton plant, especially during its development period (Ekinci & Başbağ, 2019). During dry periods, the cotton plant is exposed to water stress, which can negatively affect the plant's metabolic activities, particularly photosynthesis rates. These negative effects include a reduction in leaf area and restricted stomatal movement (Ödemiş et al., 2023). For example, in the study by Ekinci and Başbağ, the effects of water restriction on some morphological characteristics of the cotton plant were examined, and it was stated that irrigation restriction had significant negative effects on growth (Ekinci & Başbağ, 2019). Furthermore, water restrictions during the formation period of cotton fibers under drought conditions have negative effects on fiber length, strength, and maturity (Gören & Başal, 2020). Drought not only affects plant yield but also has negative effects on fiber quality. Fiber quality is particularly dependent on the availability of sufficient water during the fiber development process. Studies have shown that fiber quality decreases significantly and fiber length decreases during dry growing seasons (Gören & Başal, 2020; Tunalı et al., 2019). In particular, it has been emphasized that drought stress has a pronounced effect on the quality and yield components of cotton fibers (Gören & Başal, 2020). In areas where cotton is grown, the use of drought-resistant varieties is critical to mitigate these effects. Some studies show that developing drought-resistant cotton genotypes reduces production inputs and balances the plant's water demand (Doğan, 2020). It is emphasized that attention should be paid to the selection of such genotypes for sustainable agricultural practices under drought conditions (Doğan, 2020). Drought is an environmental factor that has serious negative effects on the cotton plant. Water stress, which directly affects the plant's growth, yield, and fiber quality, is one of the most important factors to consider in cotton farming. Water management and the use of drought-resistant varieties under drought conditions should be a priority for sustainable cotton production.

Conclusions and Recommendations

When examining the effects of climate change on cotton production, it is observed that rising temperatures negatively affect the morphological, physiological, and yield characteristics of the cotton plant. High temperatures increase the moisture deficit in the soil, leading to a decrease in cotton lint yields. Rising CO_2 levels may contribute positively to cotton plant growth in the short term by increasing the rate of photosynthesis, but in the long term, they can lead to significant declines in product quality and production volume. Drought has serious negative effects on the growth, yield, and fiber quality of the cotton plant. Water stress negatively affects the plant's metabolic activities, particularly photosynthesis rates, leading to yield losses. Given that climate change cannot be reversed in the short term, the most critical measure to be taken should be to adapt to climatic changes. Developing resilient cotton varieties suitable for changing climate conditions will reduce production inputs and balance the plant's water demand. Accurate determination of irrigation timing and monitoring of the plant water stress index are critical to preventing yield losses. The use of restricted irrigation techniques and modern irrigation methods should be encouraged. Optimizing agricultural practices such as soil conditioners and appropriate fertilization strategies can mitigate the negative effects of climate change. Supporting research studies that continuously monitor and evaluate the effects of climate change on cotton production is important to prevent future losses. Raising awareness among cotton producers about climate change and educating them on adaptation strategies is essential for sustainable cotton production. These measures are of great importance for Turkey to maintain and strengthen its strategic position in cotton production. Developing climate-resilient cotton varieties and promoting appropriate agricultural practices will play a critical role in overcoming future challenges.

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CHAPTER 11

ROLE OF MYCORHIZA ON HORTICULTURAL CROPS UNDER STRESS

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1.Introductıon

Plant stress is a critic problem affecting agricultural crops productivity. It is defined as an external abiotic (salinity, temperature, ultraviolet radiation, drought, ect...) or biotic (herbivores, insects, nematodes, fungi, bacteria, ect…) constraint that affects photosynthesis and plant's ability to convert energy to biomass thus reducing agricultural crop productivity. Mycorrhizal fungi which are a result of fungus-plant symbiotic relationship are widley inoculated nowadays in perrenials and horticultural plant production to increase yield of the host, product quality and plant's resistance to stress. The such-named symbiotic life is obtained by providing the mycorrhiza with carbon as an energy source from its host, while mycorrhiza provides their host with several benefits, one of them is resistance towards stresses(biotic and abiotic). İn this reseach we provide a comprehensive review on mycorhiza-host plant relationship and its benificial effects on perrenials and horticultural plants against abiotic stress.

The term stress in biology is derived from the concept of stress in physics, which refers to the force applied per unit area (Wardlaw, 1972). Plant stress in biology is a state where plants grows in non-ideal conditions thus applying stress on the plant. Stress effects growth, crop yield, causes perminant damage and it can even lead to death if stress exeeded plant tolerance limit. Plant stress is defined as any external abiotic(salinity, temperature, ultraviolet radiation ect...) or biotic (insects, herbivores, fungi, bacteria, nematodes ect…) constraint that decreases the rate of photosynthesis thus reducing a plant's ability to convert energy into biomass (Grime, 1977). Mycorrhizae, "Myco" is fungus and "rhiza" is root; and the word "mycorrhizae" means "fungal root". In nature, most of the plants are naturally inoculated with mycorrhiza. The AMF (abscular mycorrhiza fungi) develops non-specific symbioses with most of the plants; after approaching the roots of its host, AMF produces fungal hyphae that grows into the soil reaching more volume than roots alone can, increase nutrients, minerals and water uptake by host plant and most importantly that it protects host plants against stress. Mycorrhiza applied to the roots of perrenials is a new alternative sustainable practice against plant stress in horticulture. Many studies have examined the physiological consequences of the symbiotic relationship between mycorrhizal fungi and host plants, and the majority have demonstrated beneficial effects on plant growth, functional performance, and resistance to abiotic and biotic stresses.The such-named symbiotic life is obtained by providing the mycorrhiza with carbon as an energy source from its host, while mycorrhiza provides their host with several benefits, one of them is resistance towards stresses (biotic and abiotic). In another words, Mycorrhiza-host plant relationship is a symbiotic association. The aim of the present meta-study is to provide a comprehensive review of mycorhiza-host plant relationship and its role on perrenials and horticultural plants under abiotic stress.

2. Effect of mycorrhzia on fruit trees in orchards

The application of beneficial microorganisms represents a key strategy in sustainable agricultural systems (Vimal et al., 2017). A growing body of research has shown that these microorganisms significantly contribute to improved plant nutrition, enhanced mineral and water absorption, stimulation of vegetative and generative growth, and increased resistance to environmental stresses in horticultural crops. Mycorhiza improves plant nutrition, mineral and water intake, vegetative growth and generative growth in addition to stress resistance (biotic & abiotic) of horticultural crops. Many studies have tested the physiological effect of mycorrhiza on host plants, and most of them showed a positive influence in terms of plant function and resistance to stresses (abiotic & biotic) which will be discussed deeply below.

The use of beneficial microorganisms is considered one of the most effective strategies for achieving sustainable horticultural production systems (Vimal et al., 2017). Numerous studies have demonstrated that these microorganisms play a crucial role in improving nutrient uptake efficiency, mineral solubilization, and water absorption, thereby enhancing both vegetative and generative growth in horticultural crops. In addition, beneficial microorganisms contribute to increased plant resilience against a wide range of biotic and abiotic stresses, including drought, salinity, nutrient deficiency, and pathogen pressure.

Among beneficial microorganisms, arbuscular mycorrhizal fungi (AMF) play a particularly important role in horticultural species owing to their intimate symbiotic association with plant root systems. Mycorrhizal colonization enhances root surface area and facilitates the uptake of essential nutrients, especially phosphorus, nitrogen, and micronutrients, while also improving water use efficiency (Kuyper et al., 2021). Furthermore, AMF positively influence physiological and biochemical processes such as photosynthesis, hormonal balance, and antioxidant activity, which collectively promote plant growth and yield performance in fruit and vegetable crops (Chen et al., 2017).

Several studies have evaluated the physiological responses of horticultural plants to mycorrhizal inoculation and reported significant improvements in plant growth, yield quality, and tolerance to both abiotic and biotic stresses (Lal et al., 2023). These findings highlight the potential of mycorrhizal fungi as an eco-friendly tool for enhancing productivity and sustainability in horticultural systems. The underlying mechanisms and practical implications of mycorrhizal associations in horticultural crops are discussed in detail in the following sections.

3. Mycorhiza inoculated plants and their resistance to abiotic stress

3.1 Salinity tolerance

Salinity stress appears to be a major issue on horticultural crop productivity. Salinity conditions provokes hyperosmotic and hyperionic stresses, which causes a reduction in crop productivity and could lead to plant death. It is important to develop alternative practices to improve agricultural lands deteriorated due to salinity. Mycorrhizal fungus have been shown to improve perrenial plant tolerance to abiotic (environmental factors) stress. (Ahanger et al., 2023) reported the role of AMF as bio-amelioraters to salinity stress. Mycorrhiza applied to the roots of perrenials is a new alternative sustainable practice against salinity stress in horticulture. It is known that mycorrhizal fungi applied to plants increases the resistance toward salinity. This helps to reduce irrigation and fertalization requirements in orchards, thus minimizing the causes of secondary salinity caused by man-practices. In a study on pistacia vera, mycorrhiza reduced Na+ and Cl accumulation in leaves and roots at high salinity levels. In addition, a study reported that the use of mycorrhiza on viticulture increases tolerance to soil salinity (Trouvelot et al., 2015). Elhindi et al. (2017) reported that mycorrhizal inoculation improved photosynthetic rate, gas Exchange and chlorophyll content in *Ocimum basillicum* L. under salinit.

3.2 Drough tolerance

It is possible to develop new alternative and sustainable methods to fight agricultural lands drought, and mycorhiza grown on host plants is the new alternative sustainable practice against drought. Mycorrhiza, which lives on the hosts root system making hyphal networks, increases the absorption surface area a plant can reach, inceasing the water intake by plants thus reducing water stress. By applying mycorhiza on horticultural crops in orchards, Extremely pahalı irrigation methods could be decreased thus decreasing costs on horticultural products producers. Mycorrhizal hyphae extend into the growing media increasing the effectiveness of plant roots by improving the absorption of water and elements, expanding the surface area of roots & hyphae in soil. Mycorrhzia increases the plant root area therefore improves the uptake of water from soil resulting an increase in plant's resistance to drought and decreasing drought stress. Many researches reports improved performance of mycorrhizal plants under water stress conditions. In a reseach on Pistacia spp. subjected to high drought stress, it was found that shoot dry weight (DW) of Pistacia spp. inuclated with mycorrhzia (+M) was higher than that of the non-inoculated (-M) (Fattahi et al., 2021). In another research it was found that perrenials inoculated with mycorrhzia have better growth response under water stress than non-mycorrhizal perrenial plants. Under water dificiency, mycorhizial inoculated plants outperforme non-inoculated plants in both vegetative and generative growth (Jayne and Quigley, 2014).

3.3 Heavy metals tolerance

Heavy metals (HM) high concentration adversely affects horticultural plants and soil microorganisms. Several biological, chemical, physical and molecular processes are partly disturbed or stopped due to heavy (HM) (53 elements) contamination in soil. For horticultural plants, metal toxicity subject had been boardly reviewed (Hall, 2002; Clemens et al, 2002; Benavides et al., 2005; Misra et al., 2007). Several ways and methods(Chemical, physical and biological) are being used to remove HM toxicity from sol. Mycorrhizal fungal treatment is among common biological methods of treating heavy metals in soil. Plants inoculated with mycorrhizal fungus accumulates (HM) by storing them in fungal hyphae roots turning them immobilized thus cant be uptaken by plants. Glycoprotein (commonly known as Glomalin) which is released by AM beyond the plant rhizosphere has heavy metal binding sites making heavy metals bind and accumulate (Seneviratne et al., 2017; Gohre and Paszkowski, 2006). de Andrade et al. (2008) and Garg and Chandel (2012) reported that Cd and Zn binds on the cell Wall of Mantle hyphae, resulting growth, yield, and nutrient intake improvment in horticultural plants. Thus mycorrhiza is a biobased, low cost alternaticve tecnology for cleaning up metal contamination in soil.

3.4 Temperature tolerance

Temperature stress (extreme high and low temperatures) significally affects plants in different ways (burning of leaves, decreased biomass production, product/fruit damage, and cell death) (Wahid and Close, 2007; Hasanuzzaman et al., 2013). In general, inoculated hosts shows better growth under heat compared with non-inoculated plants (Gavito et al., 2005). A study by (Birhane et al., 2012; Chen et al., 2013) demonstrated that AMF increases plant tolerance to extreme cold stress. Moreover, (Chen et al., 2013) reported that inoculated plants shows better growth than non-inoculated under low temperatures. Thus mycorrhiza supports ornamentals under temperature stress and eventually improves their growth under extreme temperatures.

4. CONCLUSION

When the findings of this study are evaluated together with the existing literature, it becomes evident that mycorrhizal fungi play a decisive role in the growth, development, and yield performance of horticultural crops. Particularly under biotic and abiotic stress conditions, mycorrhiza–plant symbiosis enhances nutrient and water uptake, supports physiological and morphological development, and significantly mitigates adverse effects such as growth retardation, yield reduction, and quality losses. The stimulation of root development, improvement in photosynthetic efficiency, and strengthening of antioxidant defense mechanisms are among the key processes through which mycorrhizal associations enhance plant stress tolerance.

Although the effects of mycorrhizal applications have been extensively demonstrated under controlled experimental conditions, field-based studies conducted under real production environments—such as nurseries and orchards—remain limited, especially for perennial horticultural crops exposed to long-term and multifactorial stress conditions. This limitation hinders a comprehensive understanding of the practical effectiveness of mycorrhizal inoculation, including species compatibility, application rates, and interactions with environmental factors. Therefore, there is a clear need for long-term, large-scale field studies evaluating the effects of mycorrhizal inoculation across different ecological conditions, rootstocks, and cultivar combinations.

In the context of increasing climate change impacts, soil degradation, and the environmental consequences associated with intensive chemical inputs, the use of mycorrhizal fungi represents a strategic component of sustainable horticultural production. Mycorrhizal inoculation not only improves plant nutrition but also offers the potential to reduce fertilizer inputs, thereby lowering production costs and minimizing environmental pollution. Moreover, as abiotic stresses such as drought, salinity, and nutrient deficiency become increasingly prevalent, the ability of mycorrhizal associations to enhance plant resilience provides a significant advantage in maintaining yield stability and fruit quality.

In conclusion, the wider adoption of mycorrhizal fungi in horticultural nurseries and orchards is an essential step toward developing sustainable, environmentally responsible, and climate-resilient production systems. Future research should focus on optimizing mycorrhiza–plant compatibility, determining appropriate application timing and methods, and assessing long-term impacts on yield and quality. Such efforts will contribute substantially to the integration of mycorrhizal fungi as a reliable and effective biotechnological tool in modern horticulture.

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CHAPTER 12

SOIL SALINITY: A SERIOUS ISSUE ON FRUIT TREES PRODUCTIVITY

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1. Introduction

Plant stress is a critic problem affecting agrıcultural crops productivity. It is defined as an external abiotic (salinity, temperature, ultraviolet radiation, drought, ect...) or biotic (herbivores, insects, nematodes, fungi, bacteria, ect…) constraint that affects photosynthesis and plant's ability to convert energy to biomass thus reducing agricultural crop productivity. Soil salinity is one of the major stresses limiting agricultural productivity worldwide; mostly in arid and semi-arid climate regions, Turkey is located on semi-arid regions, thus salinity affects country's agricultural crop productivity. Here we revıew our understanding of salinity stress impact on fruit tree growth and fruit productıon in Turkey and worldwide.

Plant stress is defined as any external constraint that reduces the rate of photosynthesis and consequently limits the plant's ability to convert energy into biomass. These constraints may arise from abiotic factors, such as salinity, temperature, and ultraviolet radiation, or from biotic factors, including insects, herbivores, fungi, bacteria, and nematodes. Excessive accumulation of mineral ions, particularly sodium (Na^+) and/or chloride (Cl^-), in plant tissues leads to salinity stress.

According to the Food and Agriculture Organization (FAO), more than 6% of the world's agricultural lands are affected by salinity. Therefore, salinity stress represents a major global challenge for plant growth and crop productivity. Soil salinization is generally classified into primary and secondary salinity.

Primary salinity results from the long-term accumulation of salts in soils or groundwater through natural processes. These processes include the weathering of parent materials containing soluble salts and the deposition of ocean-derived salts transported by rainfall and wind. In contrast, secondary salinity arises from human-induced alterations in soil hydrological balance, particularly due to inappropriate irrigation practices, which disturb the equilibrium between irrigation water input and water loss through plant transpiration (Parihar et al., 2015).

Soil salinity poses a serious threat to agricultural productivity in both Türkiye and worldwide. Crops grown under saline conditions suffer from high osmotic stress, ion toxicity, nutrient imbalances, and poor soil physical properties. Collectively, these adverse effects lead to significant reductions in crop growth, yield, and quality.

2. Impact of salinity on plant growth

Salinity induces a range of characteristic changes in plants from the onset of salt stress through to plant maturity (Munns, 2002). To explain these responses, Munns (2002) proposed the concept of a two-phase growth response to salinity, which is discussed in detail below.

The first phase of growth reduction occurs rapidly, within minutes after exposure to salinity. This response is primarily caused by osmotic changes in the root-zone environment, leading to alterations in plant water relations (osmotic effect). The osmotic effect initially reduces the plant's ability to absorb water, closely resembling water stress conditions. During this phase, genotypic differences among plants are minimal. Following the initial rapid reduction in leaf growth, a gradual recovery in growth rate may occur until a new equilibrium is established (Munns, 2002).

The second phase develops much more slowly, over days, weeks, or even months, and is associated with the accumulation of toxic levels of salts in leaves, resulting in ion toxicity. This process can lead to leaf senescence and death, thereby reducing the total photosynthetically active leaf area. Consequently, the overall photosynthetic capacity of the plant declines, negatively affecting the carbon balance required for sustained growth and development (Munns, 2002).

3. Impact of salinity on fruit trees

Fruit production is primarily affected by excessive salt accumulation in the soil. High concentrations of salts in the root zone can be transported over time to shoots and other plant organs, where they adversely affect the growth and productivity of fruit trees through osmotic stress and nutrient imbalances (Anjum, 2008). The long-term effects of salinity on fruit trees and fruit development therefore represent an important topic for discussion.

Fruit trees are among the most salt-sensitive horticultural crops, although the degree of sensitivity varies among species. Both vegetative growth and fruit yield decline proportionally with increasing salinity levels (Maas, 1993). The salt tolerance of fruit trees is strongly influenced by cultivar and rootstock selection. Available data indicate that grapefruit, lemon, and orange are among the most salinity-sensitive horticultural species (Maas and Grattan, 1999).

Under artificial salinity conditions, reductions are observed in both vegetative and reproductive traits, accompanied by a marked decrease in overall yield. The effects of salinity on fruit trees are discussed in detail in the following section.

3.1. Vegetative growth under salinity

Salt stress declines photosynthesis and disrupts pigment biosynthesis (Parihar et al., 2015). Salinity affects Both Chls (a and b) and carotenoids at different rates (Agastian et al., 2000). Salinity also affects stomatal conductance (Netondo et al., 2004). Leave temperature significantly increases under the effect of short-term salinity (Aras and Eşitken, 2019). This increase in leaf temperature in (Aras and Esitken,

2019) may be a result of stomatal closure. On another hand, salinity effects are visibily seen on leaves such as scars and burns. When salts reaches high concentrations in leaves, leaf-loss is occured. Salinity suppress leaf internode growth as well as leaf expansion and initiation (Zekri, 1991). Decreases plant dry matter production in vegetative shoots of guava plant (Cavalcante et al., 2005). It was found that salinity had no effect on P. vera rootstock shoots in the first year after salt explosure, but significantly in the years after, reductions of apical and axillary shoot diameter were detected (Mehdi-Tounsi et al, 2017). Salinity results in a reduction of growth of leaves, stems, and roots of Pistacia vera L. with tolerance variation among rootstocks (Badami-e-zarand, Saeakhs, Ghazvini) (Haggag, 1997). In general, salt accumulates in woody tissues over years (Maas and Grattan, 1999), salt were found accumulated in wood of mature fruit trees (Maas, 2019).

Fruit trees require sufcient amount of nutrients essential for proper-growth and high yield. However, salinity stress decreases macro and micronutrients absorption by roots. An amount of nutrients can't be absorbed via roots because of bounded form of nutrients (Ashkavand et al., 2015). NaCl concentration in root zone higher than 20 mM generally reduce the vegitative growth of most fruit tree species (Ebert, 1999). Root weight and size play a major role in nutrients absorption, salinity in root zone negatively afects the root size of mango fruit trees (Elsheery et al., 2020). Salinity decreases plant dry matter production in roots of guava plant (Cavalcante et al., 2005). Thus size and weight of roots of fruit trees grown in salty areas are negatively afected, resulting poor growth as well as poor fruit productivity.

3.2. Generative growth under salinity

In fruit trees, fewer flowers account for fruit yield reduction thus affecting the overall horticultural profits of fruit orchards. Salinity severly affects flowering set which therefore reduces yield of fruit trees. It was detected that salinity reduced flowering intensity in (Prunus salicina L.) (Hoffman et al., 1989). Flowering and subcequent fruit set in ber trees were affected by osmotic stress and impaired water relations adversely (Hooda et al., 1990). Salt stress causes fruitlet drop affecting the number of fruits per tree. The response of fruit trees to salt stress vary depending on species and varieties. In a study conducted; a decrease in number of fruits per tree and a reduction in yield of (Washington Navel) orange trees was clearly detected (Haggag, 1997) while in olive trees(Olea europaea L.) fruit characteristics (fruit size & pulp:stone ratio) were not affected at all (Melgara et al., 2009).

4. Salt tolerant crops and transgenics

Selecting the most salt tolerance rootstocks is also important in fighting salinity, for example in research, Grape rootstocks (1103 P, 41 B, 140 Ru and 5 BB) plant dry mass, shoot length and leaf number were affected after exposion of different levels of NaCl, and as a result, the genotype 41 B showed the maximum tolerance index (Amphissis, Kothreiki, and Mastoidis). Genotype 41B could be an essential salt tolerance rootstock for grape vines in salinity affected areas. Differences in genetic make-up exhibit greater salt tolerance, for example it was found that polyembryonic mango rootstocks are more salt tollerance than mono-embryonic types (Schmutz and Ludders, 1992).

Transgenics was also found helpful in increasing salinity tolerance, The first transformed fruit tree by transgenics was walnut reported by (McGranahan and co-workers in 1988). After that, transgenic technology was introduced sucessfully on other fruit trees such as citrus, papaya, apple, grape, kiwi, avocado etc. An example of trensgenics, gene HAL2 (which is a gene originally isolated from yeast) has been stably integrated and expressed on Carrizo citrange (which is an excellent citrus rootstock but sensitive to salinity) and transference was successfully achieved resultlng a salt tolerant rootstock (Cervera et al., 2000).

5. The use of Mycorrhiza to improve perennials salinity tolerance

It is important to develop alternative practices to improve agricultural lands deteriorated due to salinity. Mycorrhiza applied to the roots of perrenials is a new alternative sustainable practice against salinity stress in horticulture. It is known that mycorrhizal fungi applied to plants increases the resistance toward salinity. Mycorrhizal hyphae extend into the growing media increasing the effectiveness of plant roots by improving the absorption of water and elements by expanding the surface area of roots & hyphae in soil. This helps to reduce irrigation and fertalization requirements in orchards, thus minimizing the causes of secondary salinity caused by man-practices. Mycorrhizal fungus are usually applied to roots of perennial trees in horticultural nurseries during seed sowing or sapling transplanting; In this way, ornamental plants will have greater stress resistance when transplanted to landscape/orchards (Davies, 2008). In addition, a study reported that the use of mycorrhiza in viticulture increases tolerance to abiotic stresses (salinity included), thus increases tolerance to soil salinity (Trouvelot et al., 2015). Thus mycorrhizal fungi not only increase the water & nutrient uptake of plants, but also increase the resistance of salinity.

6. Conclusion

To enhance plant tolerance to salinity stress, a comprehensive understanding of the effects of salt on plant growth and development, as well as the underlying mechanisms of salt tolerance, is required at the whole-plant, molecular, and organelle levels. Achieving this objective necessitates extensive and systematic research on salt-tolerant rootstocks across different cultivars. In addition, advances in modern biotechnological approaches are essential, particularly those enabling the direct transfer or manipulation of genes associated with salt tolerance from wild or stress-adapted species into commercially valuable cultivars with superior fruit quality.

Furthermore, the implementation of alternative and sustainable management practices to mitigate salinity stress in orchard systems is of critical importance. Although complete success in overcoming salinity stress has not yet been achieved, continued and integrated research efforts combining physiological, genetic, and agronomic approaches are expected to provide effective solutions in the future.

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CHAPTER 13

POSSIBILITIES OF USING MOSS (*Hylocomiadelphus triquetrus* (Hedw.) Ochyra & Stebel) EXTRACTS IN WOOD MATERIALS

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1. INTRODUCTION

Due to its unique properties, wood has been one of humanity's most productive resources for both building and manufacturing goods since ancient times. From a sustainability perspective, wood is understood to be the most environmentally friendly building material in terms of life cycle assessment and carbon footprint. Due to these properties, there has been an increase in the use of both solid wood and various other industrial wood products produced using technological methods, especially in developed Western countries and more recently in China and other Far Eastern countries. It is crucial that the form, size, design features, and materials of architectural structures and landscape elements constructed within natural areas are selected with this in mind. Wood continues to be the most popular material used in these areas (Akarca *et* al., 2023).

Today, few materials can be used as efficiently as wood throughout its life cycle, from production to recycling. Trees store carbon dioxide throughout their lives, and they continue to do so when they reach the end of their lifespan and are cut down to become wood. Therefore, ways are being sought to achieve global goals such as "zero carbon emissions" and "Net Zero," particularly in the energy and construction sectors (UN, 2023). In this process, the time people spend at work is decreasing, while the time they have for themselves, especially in developed countries, is increasing. The idea that this increased time should be spent returning to nature, creating cleaner environments and more sustainable conditions where aboveground and underground resources are used efficiently, is gaining more support, and solutions are being developed in this direction (Manzini and Jégou, 2003). Similarly, we can say that wood finds widespread use in bridges and crossings. Impregnated solid wood is seen in the construction of numerous bridges, completely exposed to the elements. It's no coincidence that wood, another natural material, best harmonizes with the green texture in botanical gardens. While the importance of color harmony in garden design is emphasized, wood stands out as a material whose color palettes harmonize with the natural vegetation and whose texture also complements it (Köylü and Yılmaz, 2021).

All animals, plants, and humans in nature are the product of a balance. In mythology, plants are considered the most precious gift the gods have given to humanity. All plants serve humanity, and humanity's relationship with plants has been inextricably linked since its inception (Gezgin, 2006). Particularly after the 1990s, the discovery of new uses for medicinal and aromatic plants and the increasing demand for natural products have led to a gradual increase in the volume of these plants used. The current market for medicinal plants is estimated to be worth approximately $60 billion annually (Kumar, 2009). Medicinal and aromatic plants encompass a vast area in terms of both their active ingredients and areas of consumption. While there is no standardized classification for this purpose, they can generally be grouped according to their families, active ingredients, consumption and use, organs used, and pharmacological effects. While synthetic preparations, such as atebrin, are used in the treatment of malaria, quinine, derived from the chinchona tree grown in the tropics, remains of great importance (Ceylan, 1995).

The primary objective of this research is to develop environmentally friendly and sustainable impregnation solutions and to determine their effects on wood. In this context, the potential use of boric acid and moss (Bryopsida) extract in impregnation processes on chestnut (*Castaneasativa Mill.*), a naturally durable wood, was investigated, and adhesion and air-dry specific gravity changes on the wood were determined.

2. MATERIAL AND METHOD

Chestnut wood (*Castaneasativa Mill.*) and scoth pine (*pinus*), a naturally occurring species in Turkey known for its durability, was chosen for this study. Its fiber structure and high resistance to decay and fungal damage make it a popular choice for outdoor applications. The sapwood samples used in the experiment were prepared in accordance with TS ISO 3129. Moss extract, a natural resource and a medicinal and aromatic plant, was subjected to a dual-process impregnation with a boron derivative.

2.1. Experimental Sample Preparation

In this study, chestnut /scoth pine wood selected for impregnation applications was prepared from the sapwood portions, which were smooth, flawless, homogeneous in density and color, free of reaction wood, and free from insect and fungal damage. Test samples were prepared in accordance with the principles specified in the TS ISO 3129 standard. TS 2471-2472 principles were followed in determining air-dry specific density.

2.2. Impregnation Process

The impregnation process used a dipping method. Accordingly, completely dry test samples were dipped in moss plant extract and boric acid (a natural preservative) for 30 minutes (short-term). (Var 1994).

2.3. Plant Extract Preparation (Moss Extract)

The After weighing the specified weights, the moss samples to be used in the study were heated in 200 ml of hot distilled water (or water of equivalent purity) in a reflux system for 1 hour, below the boiling point. The mixture was stirred at regular intervals throughout the heating process. Upon completion of the process, the sample was placed in a pre-prepared porous capsule and filtered under vacuum. The flask was washed several times with distilled water to ensure no sample remained in the flask, leaving the insoluble portions completely within the porous capsule (Ceylan, 2020).

2.4. Retention (%)

Using samples that were completely dry before and after the impregnation process, the amount of impregnation solution absorbed by the wood (% retention) was determined with the help of the equation given below. % Retention R(%)=Moes– Moeö/ Moeö *100 Moes= Complete dry weight after impregnation (g) Moeö= Complete dry weight before impregnation (g) (Baysal 1994).

3. FINDINGS AND DISCUSSION

3.1. Extract (Solution)

Solution properties are given in Table 1.

Table 1. Properties (Extract)

Plant extract (Moss)	Solvent	Degree (ºC)	pH		Density (g/ml)	
			EÖ	ES	EÖ	ES
Boric acid 1%	Water	22ºC	5.15	5.15	1.025	1.025
Moss Extract 1%			5.63	5.63	0.885	0.885

Bİ: Before impregnation **Aİ**: After impregnation

No changes were observed in pH and density during impregnation applications. This may be due to the solution structure.

3.2. % Retention

The amount of material retention to wood material is given in Table 2.

Table 2. % Retention

Wood Type	İmpregnation Material (%1)	Retention (%)	HG
Chestnut	Moss Extract+Boric acid	0.65	B
Scoth pine		0.89	A

The highest adhesion amount was found in Scots pine wood (0.89%), while the lowest adhesion amount was found in chestnut wood (0.65%). This may be due to the structure of the black moss extract, wood type, impregnation method, wood anatomy, and solution concentration.

3.3. Air Dry Specific Density (g/cm^3)

Air Dry Specific Density are given in Table 3.

Table 3. Air Dry Specific Density (g/cm^3)

Wood Type	İmpregnation Material (%1)	Density (g/cm^3)	HG
Chestnut	**Control**	0.55	A
	Moss Extract+Boric acid	0.49	C
Scoth pine	**Control**	0.52	B
	Moss Extract+Boric acid	0.46	D

The highest air-dried specific gravity was determined in chestnut wood (0.49 g/cm^3), and the lowest air-dried specific gravity was determined in scots pine wood (0.46 g/cm^3). Compared to the control sample, the air-dried specific gravity value for both wood types was lower in the impregnated material.

4. CONCLUSION

This study contributes to the literature by comparatively demonstrating the results of impregnation processes in different species. The findings may guide both the selection of appropriate species and process parameters for industrial applications and the production of wood materials with increased durability. However, the study is limited to specific species and specific impregnation conditions. Future research should evaluate a wider range of species, different chemicals, and alternative impregnation methods (e.g., vacuum-pressure systems or nanoparticle-based solutions). Furthermore, long-term durability tests, environmental effects (humidity, temperature, biodegradation, etc.), and economic analyses should be conducted. This will allow for a more comprehensive understanding of the performance of impregnation processes under both laboratory and field conditions.

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CHAPTER 14

EFFECTS OF BORIC ACID AND MOSS APPLICATION ON SOME TECHNOLOGICAL PROPERTIES OF WOOD MATERIAL

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1. INTRODUCTION

Due Throughout human history, trees have been an integral part of life and one of nature's most important gifts. Trees have contributed to human society both physically and spiritually. They have played a significant role in the formation and development of civilizations. They have provided people with protection from the elements, creating a safe living space. Throughout human history, trees have been an important raw material used in many areas such as shelter, fuel, tools, and more. Over time, the uses of trees have expanded, and they have become one of the fundamental materials contributing to the development of civilizations. Wooden furniture has become a symbol of wealth and status in ancient, Egyptian, Roman, and medieval Europe.Today, trees constitute the fundamental raw material of the furniture industry (Yılmaz, 2022). Alkan (2016), scots pine wood (*Pinus sylvestris L.*) was impregnated with boron compounds such as boric acid, borax, borax+boric acid, and tannin-rich natural impregnants (kebroka and tara) at concentrations of 1%, 3%, and 5%. As a result of the study, maximum screw retention and bending strengths were recorded in samples impregnated with kebraka in solutions impregnated with a maximum full dry specific gravity of 5%. Furthermore, significant increases were observed in compressive strength and modulus of elasticity, especially in the 3% borax and boric acid combination. The obtained data indicate that the use of natural impregnants with boron compounds positively improves the mechanical and physical properties of wood.

Past, uninformed practices, along with current, flawed approaches, threaten many species, disrupting the ecological restoration cycle and accelerating the rate of species extinction. Ecological restoration is a process that aims to restore ecosystems in degraded areas. The primary objectives in this process are the protection of existing species, the maintenance of biodiversity, and the restoration of the ecosystem to its former functional state. In every interaction with nature, preserving the natural environment and providing suitable habitats for all living things should be a priority (Gökkür and Şahin, 2015). Similarly studies on the effects of impregnated wood on biological durability have shown that natural wood samples were used as the wood/wood type; natural or water-soluble impregnants were used as the impregnation materials; and pressure-applied methods were used as the impregnation methods. In the same thesis, studies on the effects of wood on combustion properties have shown that both natural and artificial wood samples were used as the wood/wood type; natural, oily, water-soluble, and organic solvent-based impregnation materials were used as the impregnation materials; and both pressure-applied and non-pressure-applied methods were used as the impregnation methods (Öztürk, 2024).

All Density, flexural strength and modulus of elasticity of red pine wood treated with some geothermal waters: a study in Konya Region was investigated In the impregnation solutions prepared using geothermal waters, 6 different impregnation solutions were prepared at normal room and source outlet temperatures and applied separately to the wood samples. Density, flexural strength and flexural modulus of elasticity were examined in the control sample without impregnation and the impregnated wood samples. As a result of the test, it was determined that the density increased, but the modulus of elasticity and flexural strength values decreased. The highest retention value was obtained in the impregnation solution prepared with water at 40.90 C taken from the SJ-5 geothermal well. It was observed that the density of these wood samples increased by 16.64%, the flexural strength decreased by 3.17% and the modulus of elasticity decreased by 29.06% (Kaplan and Var, 2019).

The rapid decline of forest resources and the exposure of humankind to synthetic/chemical influences in the environment they inhabit pose serious threats. Natural plants are used for a wide variety of purposes (medicine, cosmetics, food, spices, agriculture, livestock, spices, the paint industry, etc.); by impregnating organic wood with boric acid, a dual process with moss extract, which has been identified for its antioxidant/antibacterial properties, has been used to determine some of its technological properties and to create a hygienic structure in the wood.

2. MATERIAL AND METHOD

The study used wood from Scots pine and chestnut, which are found in widespread stands in Turkey. The wood used in the study was first cut into slats, then cut radially to produce sapwood pieces. The wood samples used in the experiments were prepared according to TS ISO 3129 and impregnated with boric acid and kelp.

2.1. Experimental Sample Preparation

Chestnut and scots pine wood used in impregnation processes was prepared from sapwood sections that were free of cracks, knots, straight fibers, and free of any growth defects or gauze formations; homogeneous in density and color; free of reaction wood; and unaffected by insect and fungal damage. Samples prepared for mechanical testing were taken in accordance with relevant standards, and the tests were conducted using the Universal Testing Machine (Bozkurt et al.1996-1997, TS 2470-2471)

Figure 1. Test Examples

2.2. Impregnation Process

The impregnation process used a dipping method. Accordingly, completely dry test samples were dipped in moss plant extract and boric acid (a natural preservative) for 30 minutes (short-term). (Var 1994).

2.3. Plant Extract Preparation (Moss Extract)

The After weighing the specified weights, the moss samples to be used in the study were heated in 200 ml of hot distilled water (or water of equivalent purity) in a reflux system for 1 hour, below the boiling point. The mixture was stirred at regular intervals throughout the heating process. (Ceylan, 2020).

2.4. Static Bending Strength

In measuring the bending resistance, the procedures defined in the TS ISO 13061-3 (2021) standard were taken as basis, and test samples with dimensions of 20 * 20 * 300 mm were prepared as shown in Figure 2.

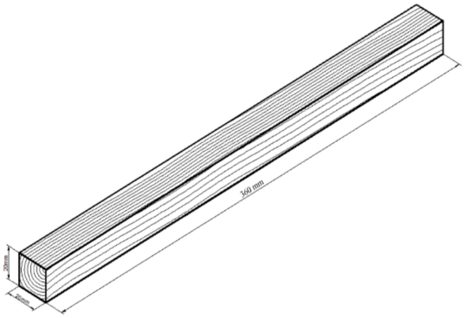

Figure 2. Bending Strength Example.

2.5. Static Dynamic Bending Strength (shock)

Dynamic bending (shock) resistance tests were carried out in accordance with TS 2477 (1976). Samples were prepared with dimensions of 20*20*300 mm and then acclimatized to 20 ± 2ºC and 65 ± 5% relative humidity, with wood moisture content at 12%.

3. FINDINGS AND DISCUSSION

3.1. Extract (Solution)

Solution properties are given in Table 1.

Table 1. Properties (Extract)

Plant extract (Moss)	Solvent	Degree (ºC)	pH		Density (g/ml)	
			EÖ	ES	EÖ	ES
Boric acid 1%	Water	22ºC	5.15	5.15	1.025	1.025
Moss Extract 1%			5.63	5.63	0.885	0.885

3.2. Static Bending Strength (N/mm^2)

Bending strength test results are given in Table 2 and Figure 3.

Table 2. Static Bending Strength (N/mm^2)

Wood Type	İmpregnation Material (%1)	Static Bending Strength	HG
Chestnut	**Control**	90.56	B
	Moss Extract+Boric acid	81.50	C
Scoth pine	**Control**	80.15	D
	Moss Extract+Boric acid	115.80	A

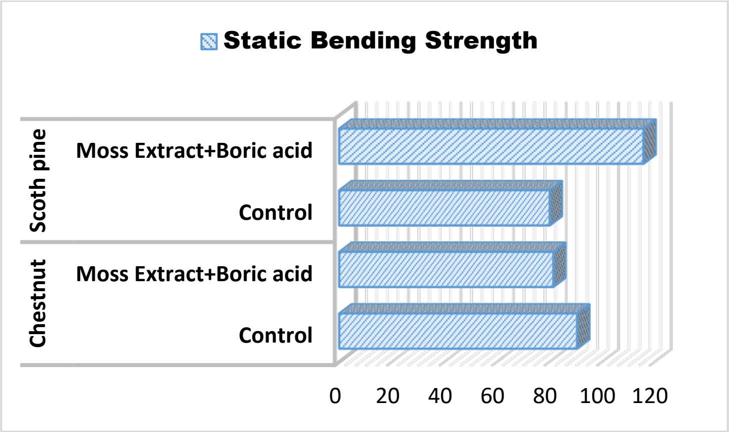

Figure 3. Change of Static Bending Strength (N/mm^2)

The highest bending strength was determined in Scots pine wood with moss+boric acid (115.80 N/mm^2), while the lowest bending strength was determined in the scots pine wood (80 N/mm^2) control sample. This may be due to the anatomical structure and wood type of the wood.

3.3. Static Dynamic Bending Strength (shock)

Static dynamic bending strength test results are given in Table 3 and Figure 4.

Table 3. Dynamic Bending Strength (N/mm^2)

Wood Type	İmpregnation Material (%1)	Dynamic Bending Strength	HG
Chestnut	**Control**	0,57	B
	Moss Extract+Boric acid	0,61	A
Scoth pine	**Control**	0,46	D
	Moss Extract+Boric acid	0,49	C

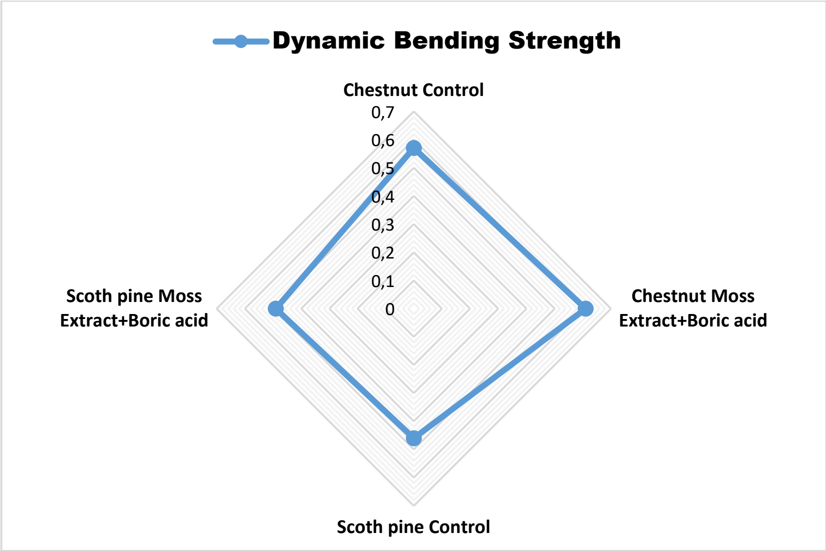

Figure 4. Change of Dynamic Bending Strength (N/mm^2)

The highest dynamic bending strength was determined in chestnut wood with moss+boric acid (0.61 N/mm^2), while the lowest dynamic bending strength was determined in the Scots pine wood control sample (0.46 N/mm^2). This may be due to the wood type, anatomical structure, and impregnation material.

4. CONCLUSION

Medicinal and aromatic plants obtained from our country's resources have been used in a wide variety of areas, as well as in all indoor and outdoor spaces intertwined with wood. This study demonstrates the potential for organic wood to be used in conjunction with wood, both indoors and outdoors. In line with human and environmental health awareness, organic wood has become more valuable and hygienic by impregnating it with extractives (antibacterial/antioxidant). The technological extractives, in particular, have demonstrated positive properties. It can be used in hospitals, pharmacies, all environments requiring cleanliness and hygiene, and, more importantly, in children's toys and playgrounds. In addition to determining technological properties, it is particularly beneficial to conduct TGA (Thermogravimetric Analysis) tests. Water uptake rates, water repellency values, and the amount of washed-out material can be checked in all spaces intertwined with water.

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